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# STUDIES OF THE WATERS ON THE CONTINENTAL SHELF, CAPE COD TO CHESAPEAKE BAY

## II

## Salinity

BY

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## INTRODUCTION

The present paper forms a sequel to the account of the temperature of the same region (Bigelow, 1933). Messrs. E. W. Bailey, Henry Sears, and O. E. Sette assisted in the analysis of the data.

## HISTORY AND SOURCES OF INFORMATION

Data for the salinity of the region are not as extensive as for its temperature: especially must we regret the fact that salinities have not been included in the daily observations at Lightships which have proved so instructive for temperature (Rathbun, 1887; Parr, 1933).

The most extensive sources of information, from the synoptic standpoint, and the only sources that meet modern requirements of accuracy for the underlying strata of water, are the serial observations taken on cruises by the vessels of the U. S. Bureau of Fisheries, since 1913; of the U. S. Coast & Geodetic steamer "Bache," 1914; and of the Research ship "Atlantis" of the Woods Hole Oceanographic Institution, 1931 and 1932. Station data have already been published, as follows: "Grampus" cruises of 1913–14, and 1916, (Bigelow, 1915, p. 344, 1917, p. 330, and 1922, p. 176); "Bache" cruise of 1914–1915, (Bigelow, 1917a, p. 55); "Albatross" cruise of 1920, (U. S. Bureau of Fisheries, 1921, p. 154); "Albatross II" and "Atlantis" cruises of 1927–1932, (Bigelow, 1933, p. 104).[1] A considerable number of serial observations were also taken in the summers of 1927 and 1928 by Mr. C. O. Iselin, on the schooners "Chance" and "Atlantis I" (Iselin, 1930). These data are tabulated below (p. 91). And salinities for the mouth of Delaware Bay and along the coast of New Jersey, taken by Professor A. E. Parr, during biological investigations of the U. S. Bureau of Fisheries, are noted, in the following pages, in the appropriate connections.

In the summer of 1889, a large number of determinations of density, by floating hydrometer, were made in the offing of New England, by Libbey (1891, p. 413); those for the surface agreeing on the whole with more recent determinations (p. 59). But his subsurface readings yield salinities so high that they cannot be taken into account.[2]

Dickson's (1901) tabulation of salinities for the North Atlantic, based on titration of surface samples collected on commercial steamship routes, for the years 1896 and 1897, includes scattering observations from the American continental shelf. Many data, of similar source, since 1907, are also to be found in the hydrographic tables, published annually by the International Council for the Exploration of the Sea (Conseil Internat., 1909–1933). And while these data are scattered, both as to date and as to precise locality, the fact that the great majority were taken along (or near) a line New York-Nantucket lightship, makes them available for the calculation of monthly averages, for this part of the shelf.

All of these sources have been drawn upon, in the preparation of the following report.

[1] A few of these latter readings are obviously erroneous hence have been omitted from consideration in the present report.

[2] For further discussion of these data, see Bigelow, 1915, p. 244.

## GEOGRAPHIC LIMITS

The present study is confined to the continental shelf between the offings of Cape Cod (longitude about 70°) and Chesapeake Bay;—extended southward, for occasional months, to the offing of Cape Hatteras; and with such discussion of conditions along the continental slope as is justified by occasional profiles. For a summary of the topography of the region (Fig. 1 A), see Bigelow, 1933, p. 6.

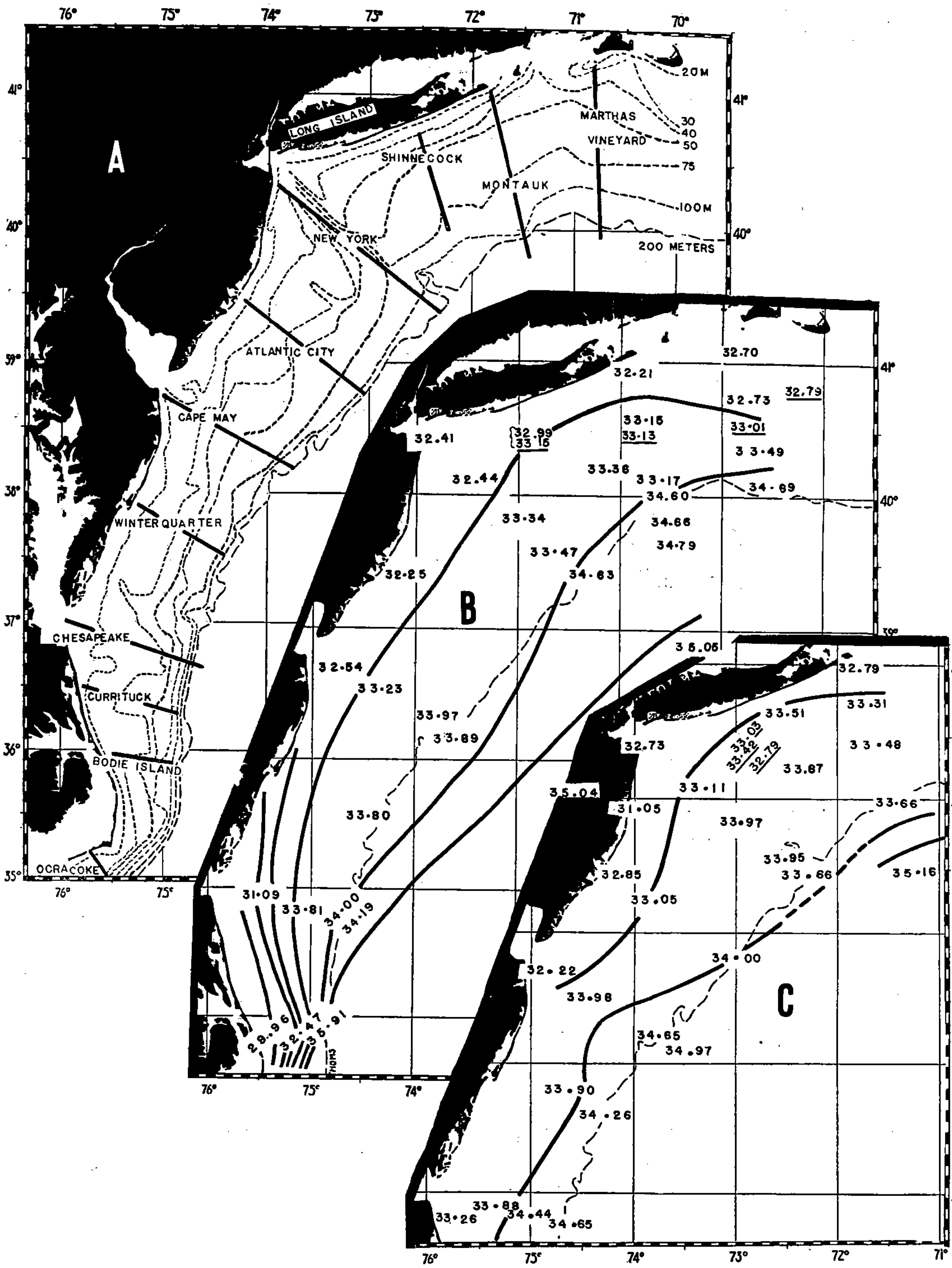


FIG. 1.—A, Locations of Profiles; B, Salinity at the surface, February 5–13, 1930; C, Salinity at the surface, February 24–March 5, 1929. Broken lines mark the bottom contours. Underlined numbers are from Int. Conseil, 1910–1932.

# SALINITY

## LATE WINTER

In the coastal waters of eastern North America, to the north of the latitude of Cape Hatteras, the late winter, or (according to locality) early spring, is a convenient starting point for a description of the cycle of salinity (just as for temperature) because the surface salinity is then close to its maximum for the year (just as temperature is at its minimum), preceding the considerable decrease which follows the coming of the rivers into freshet.

General surveys of the region, for the late winter, were carried out in two years only;[3] a partial survey in 1931. Individual profiles were also run in 1928 and 1932, and scattered observations are available, for several years, on steamship lines entering New York (p. 3). These, in combination, may be accepted as representing the normal state for the season, as only minor variations appear from year to year.

*Surface.* The basic feature in the pattern of salinity of the region, the year round, (as for coastwise regions in general, where the inflow of water from the land is considerable) is that isohalines tend to parallel the coastal trend, with values increasing continuously from the shore, seaward, along any given profile normal to the coast. The surface charts, for the late winters of 1929 and 1930 (Fig. 1 B, C), combined with more scattered data for the other winters, also show a decidedly uniform pattern, there being no pronounced fans of low salinity off the several bays and rivers, nor any well-marked overflows of highly saline water from offshore. At most, expansion of low values, from inshore, is indicated along shore from Chesapeake Bay southward, and of intermediate value in the offing of Martha's Vineyard; while on the other hand, water of high salinity comes progressively closer to the coast from north to south, corresponding to the narrowing of the continental shelf.

Proceeding from the shore seaward, we find surface salinity at the innermost stations from the Cape Cod to the Chesapeake Bay profile, averaging about 32.3 ‰ (31.09 ‰ to 33.26 ‰). Somewhat lower mean values no doubt prevail immediately next the coast line, judging from readings of about 30.00 ‰ off Bodie Island, February 11, 1930; of 31.8 ‰ on Five Fathom Bank, of 31.36 ‰ and 31.02 ‰ close in to Wildwood, New Jersey, on February 16–19, 1931;[4] of 31.05 ‰ close to the New Jersey coast, on March 2, 1929 (Fig. 1 C). And the considerable variation to be expected at this time of year off the mouths of bays and inlets, from year to year (dependent on the amounts of fresh water being discharged), is indicated by the wide difference off the mouth of Chesapeake Bay between February 10, 1930 (31.09 ‰), and March 4, 1929 (33.26 ‰).

The mean surface value for February is about 1.2 ‰ higher along the mid-belt of the continental shelf (about 33.5 ‰:—observed range 32.7 ‰–34.4 ‰) than inshore and on the whole more uniform, as illustrated by the fact that 19 out of 23 determinations for four different years have fallen within a range of 0.86 ‰ (33.11 ‰–33.97 ‰). Along the line New York-Nantucket Lightship the February mean, for all years, has been about 33.1 ‰, or very slightly lower than the mean for January (33.2 ‰, p. 75). At the edge of the continent, close to the 200 meter contour line, the mean surface value for the month is about 34.1 ‰; the recorded range about 1.2 ‰ (33.48 ‰–34.69 ‰). And during each February of record, the isohaline for 34 ‰

[3] 1929, February 24–March 5; 1930, February 5–13.
[4] Data supplied by A. E. Parr.

has roughly paralleled the edge of the continent, as defined by the 200 meter contour (Fig. 1 B, C); in 1930 it followed the latter quite closely; in 1929 it lay some 20 miles further offshore in the northeastern sector; as far inshore in the southern.

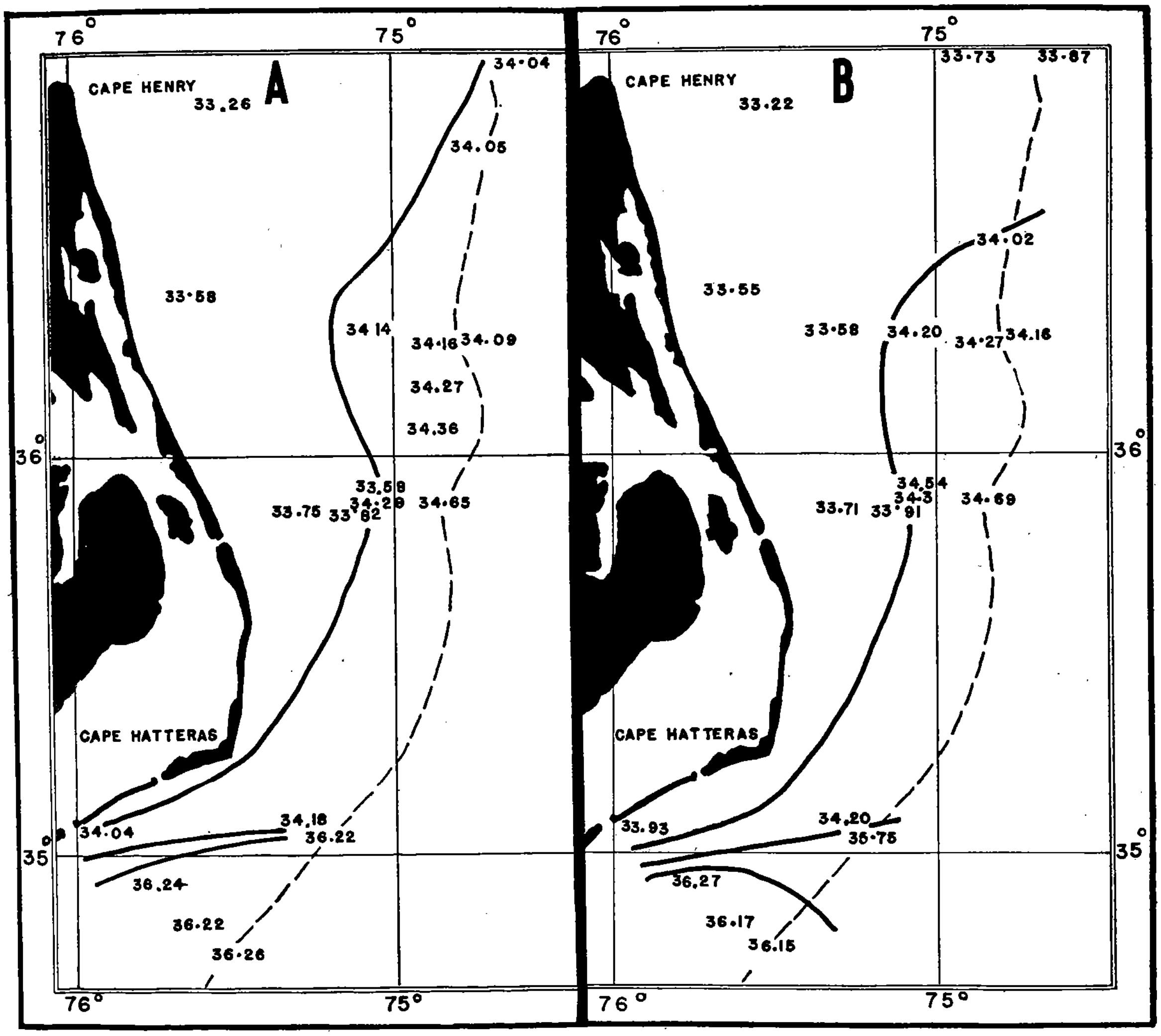


FIG. 2.—Salinity in the vicinity of Cape Hatteras, February 22–26, 1931:—A, surface; B, near the bottom.

The February cruises of 1929 and of 1930, combined, show that there are considerable secular differences in the breadth of the band of surface water of 34 °/₀₀–35 °/₀₀ at this season; consequently in the distance from the continental edge out to the isohaline for 35 °/₀₀. In 1930, this belt decreased in breadth from about 45 miles in the offing of New York to 15–20 miles off Chesapeake Bay (Fig. 1 B); whereas in 1929 it was only about 12 miles wide off New York, but upwards of 35 miles wide off Cape May.[5]

[5] The Chesapeake Bay profile for that year did not extend out far enough to reach surface water as saline as 35 °/₀₀.

Available data (Dickson, 1901; Bigelow, 1927) show that the salinity of the continental shelf on the whole decreases, from the Martha's Vineyard profile eastward, at this season. In 1920, for example (Bigelow, 1927, Fig. 91), the isohaline for 33 ‰ lay some distance out from the continental edge even at latitude 69°; at least 90 miles out from the 200 meter contour line and 140 miles out from the land in the offing of southern Nova Scotia. And while Dickson's (1901) charts show it as crossing Georges Bank in February of 1896 and 1897 (i.e., somewhat nearer the coast), this contrasts with a location only mid-way out on the shelf (45 miles out from the land) off New York. Similarly, water less saline than 32.5 ‰ occupies a relatively much broader inshore belt in the Gulf of Maine and off southern Nova Scotia than anywhere to the west of Cape Cod (cf. Fig. 1 B, C, with Bigelow, 1927, Fig. 91), with corresponding difference between mean salinities for the shelf as a whole. This west-east gradation is, however, a gradual one at this season, there being no abrupt transition in salinity anywhere between the offings of Chesapeake Bay and of Nova Scotia.

This same type of distribution also extends in the opposite direction (i.e., southward) nearly to Cape Hatteras, except that, with the narrowing of the shelf, the transition between lower values inshore (30.00 ‰–33.5 ‰) and higher (>34 ‰) offshore becomes condensed within a narrower belt (only about 20 miles wide, off Chesapeake Bay in 1929 and 1930), and that surface water more saline than 35 ‰ may encroach on the shelf near latitude 36° in some winters (Fig. 1 B), though not in others (Fig. 1 C). In the immediate vicinity of Cape Hatteras, however, the observations for February 1931, (Fig. 2) show a north-south transition to much higher values, no less abrupt for salinity than for temperature (Bigelow, 1933, p. 11, Fig. 4), water of 34 ‰ lying within 3 or 4 miles of the coast some 20 miles south of the cape, and with surface values higher than 36 ‰ halfway in across the shelf there. According to the data for that year, this transition belt is most abrupt close to latitude 35° (some 15 miles south of Cape Hatteras), where a change of more than 2 ‰ was recorded within a north-south distance of not more than 6 miles.

As this abrupt north-south transition extends down to the bottom, we may forestall the account of subsurface conditions, by pointing out that this encroachment of oceanic water more saline than 36 ‰ and warmer than 18° not only entirely pinches off the slope water, which intervenes between the continental edge and oceanic water from Cape Hatteras northward, but even reduces the coastal water to insignificance. Consequently, the belt of the latter type to the southward along South Carolina and Georgia, has no structural connection with the coast water to the north of Cape Hatteras.

*Mid-depths.* In February, the salinity averages close to homogeneous vertically from surface to bottom, over the whole mid-zone of the continental shelf, from the offing of Martha's Vineyard, south at least to latitude 36° N., and seaward about to the 70 meter contour line. In this, salinity agrees with temperature—as might, indeed, have been expected at this time of year, when the water has little vertical stability.

Even in the inshore belt, exceptions are to be seen at this season only at stations where low surface salinities show the immediate effects of land water. Off the mouth of Chesapeake Bay, for example, and close in to the coast to the southward, in 1930, very low surface values (Fig. 1 B) were associated with very steep vertical gradients of 1.7 ‰–3.00 ‰ per 20 meters depth (Fig. 3 A). Comparatively steep gradients of 1.2 ‰ and 0.8 ‰ per 20 meters respectively, were also recorded near shore off Barnegat and off New York in 1929; and are to be expected locally off the mouth of Delaware Bay, and at the mouth of Long Island Sound. Apart from localities showing this local surface freshening, the mean vertical gradient, in both years combined, out to the 90 meter contour line, and from surface to bottom is only about 0.08 ‰ per 20 meters of vertical distance, the maximum per 20 meters, only about 0.3 ‰.

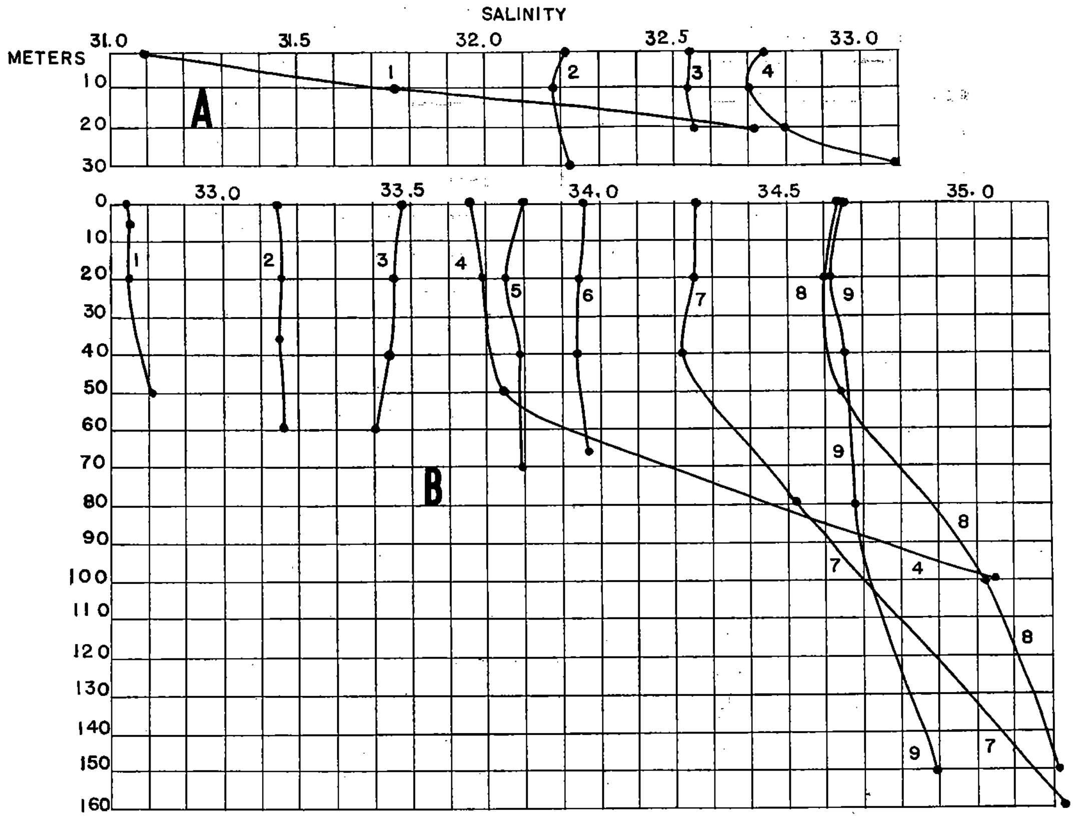


FIG. 3.—Vertical distribution of salinity, February–March:—A (above) inshore:—(1) sta. Chesapeake Bay I, February 10, 1930; (2) sta. Montauk I, February 7, 1930; (3) sta. Cape May I, February 8, 1930; (4) sta. New York I, February 28, 1929. B (below) offshore:—(1) sta. Martha's Vineyard II, February 5, 1930; (2) sta. Montauk II, February 6, 1930; (3) sta. Montauk III, February 26, 1929; (4) sta. New York V, February 27, 1929; (5) sta. Winterquarter III, February 9, 1930; (6) sta. Cape May III, February 9, 1930; (7) sta. Winterquarter III, March 3, 1929; (8) New York V, February 7, 1930; (9) sta. Cape May IV, March 4, 1929.

Near the edge of the continent, conditions become less uniform as the slope water is approached. In the 90–250 meter contour belt as far southward as the Chesapeake Bay profile, the February stations for 1930 showed a considerable increase in salinity with depth, below the nearly homogeneous superficial stratum (Fig. 3 B), which there varied from about 20 meters to about 50 meters in thickness. But in 1929, when two of the stations in this belt were of this same type (New York and Winterquarter profiles) the salinity at others, on either side of them, was close to homogeneous vertically in the deeper strata. And still a third type of vertical distribution for this belt (so far not found further north) is illustrated by the offshore station on the Bodie Island profile for

1930 (Fig. 8) which shows the presence of an overflow of oceanic water of high salinity (>35.8 °/₀₀) in the uppermost 40 meters.

Still farther out to sea, over the upper part of the continental slope, the vertical gradient is very evidently governed by the depth at which lower salinities, from inshore

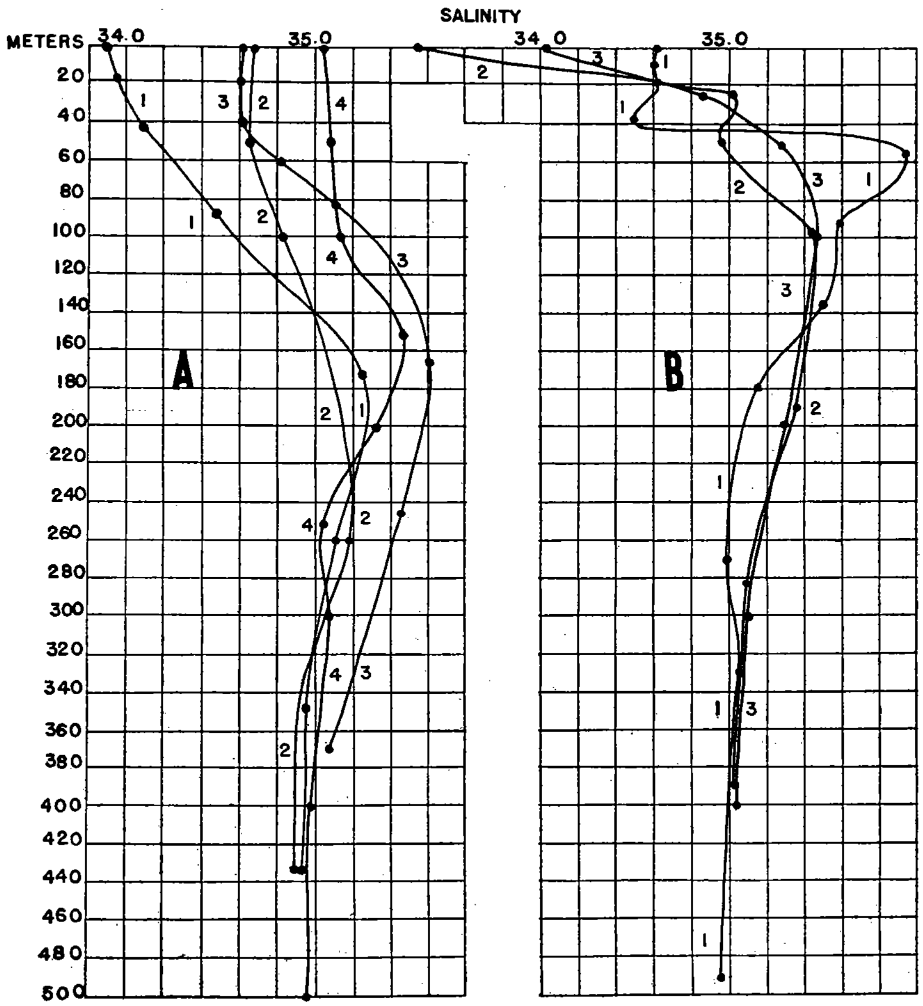


FIG. 4.—Vertical distribution of salinity along the continental slope:—A, February:—(1) sta. Cape May V, February 9, 1930; (2) sta. Montauk V, February 6, 1930; (3) sta. Chesapeake Bay IV, February 12, 1932; (4) sta. Cape May VI, February 12, 1930. B, July–September:—(1) sta. Montauk VI,* July 24, 1929; (2) sta. New York V, September 6, 1932; (3) sta. Cape May V, September 4, 1932.

and higher from offshore interdigitate, in the mixing process that is constantly in operation there (Fig. 4). In most cases the salinity at these offshore stations over depths greater than 1000 meters, has been highest at about the 150–175 meter level, decreasing slightly with increasing depth to about the 300 meter level, below which there is little further

* Curve should pass through 35.50 at 38 meters instead of 34.50.

change;—also decreasing toward the surface with a gradient of varying steepness (Fig. 5 A). In three instances, however (Martha's Vineyard profile, 1930, Cape May and Montauk profiles, 1929), the outermost stations have lain in a belt where salinity was close to homogeneous vertically, from the surface right down to 900–1000 meters.

It follows, from the types of vertical distribution just described, that horizontal

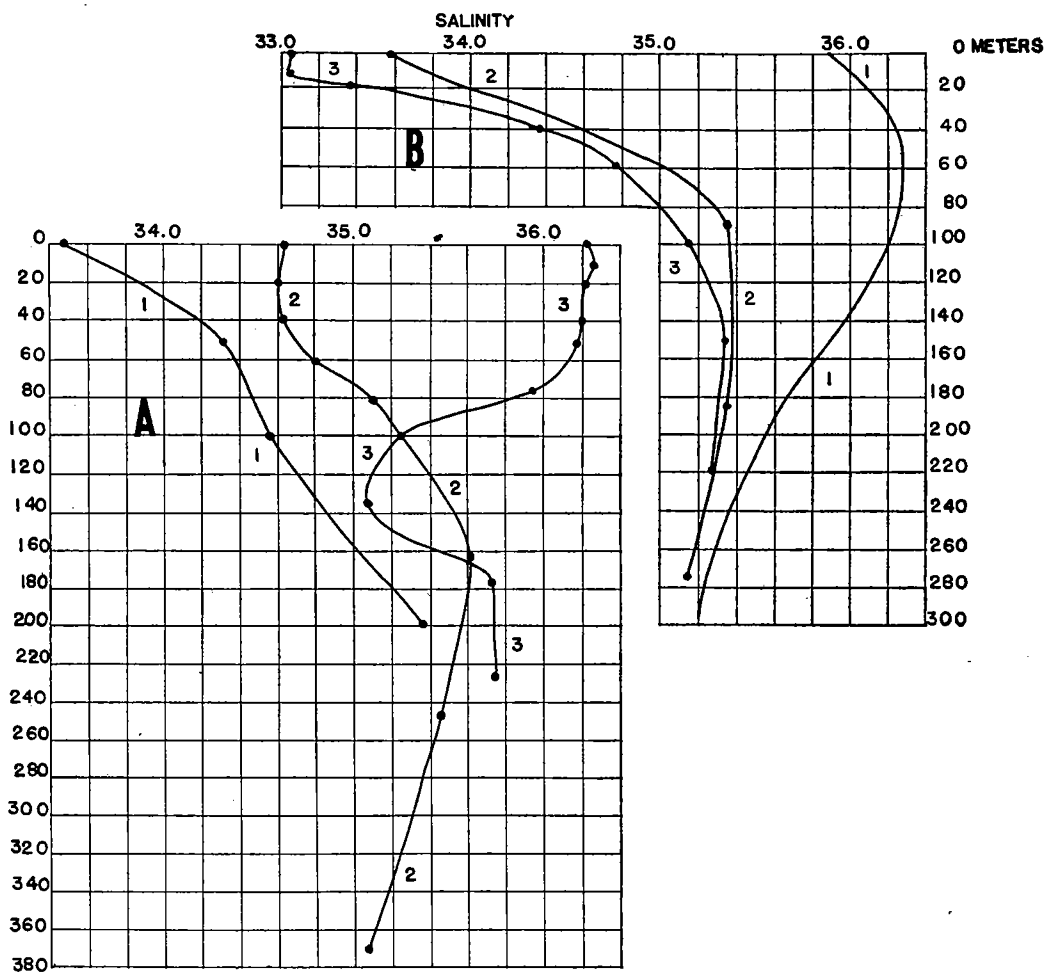


FIG. 5.—Vertical distribution of salinity:—A, for February at (1) stations Martha's Vineyard VI, February 18, 1931; (2) Chesapeake Bay IV, February 12, 1932; (3) Cape Hatteras II, February 23, 1931. B, for June-July:—(1) at 300 meter contour line off Cape Hatteras, June 21, 1927, scaled from profile; (2) off Chesapeake Bay, near 300 meter contour, July 24, 1913 (Bigelow, 1915, sta. 10076); (3) sta. Martha's Vineyard IV, July 13, 1930.

projections of salinity show much the same pattern out about to the 70 meter contour line, and close to the same actual values, at any chosen depth as at the surface, except that the surface freshening at inshore stations is not apparent deeper than about 20 meters. In most cases this homogeneity is correspondingly illustrated in profiles, by the presence of a band of considerable breadth, along the mid- or outer belt of the shelf,

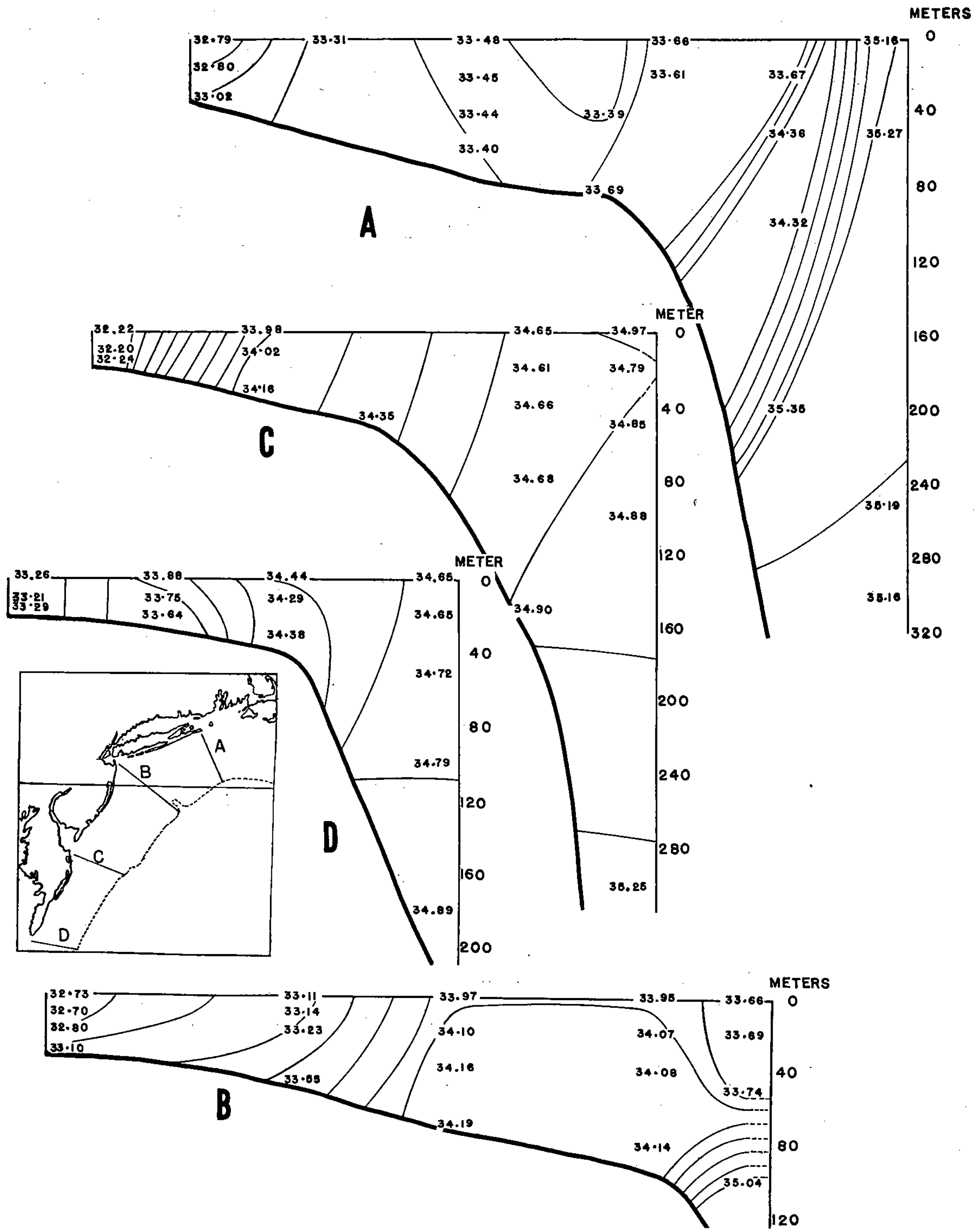

FIG. 6.—Salinity profiles crossing the continental shelf, February–March:—A, off Montauk, February 25–28, 1929; B, off New York, February 28, 1929; C, off Cape May, March 3–4, 1929; D, off Chesapeake Bay, March 3–4, 1929.

within which but few isohalines are included between surface and bottom at any given locality, with these few either shown as closer to perpendicular than to horizontal, or showing various undulations, depending on small differences from station to station.

This state may extend close in to the shore (Fig. 6 A, D), or it may give place there to a situation where very many more isohalines are included between surface and bottom; or at least, when there is abrupt horizontal transition of the same order (Fig. 6 C). Extreme examples of this type are illustrated by the Bodie Island and Chesapeake Bay profiles for February, 1930 (Fig. 7 B, 8 A).

Along the outer zone of the shelf, between, say, the 70 meter and 150 meter contour lines, the transition, characteristic of the season, between homogeneity in the upper layer,

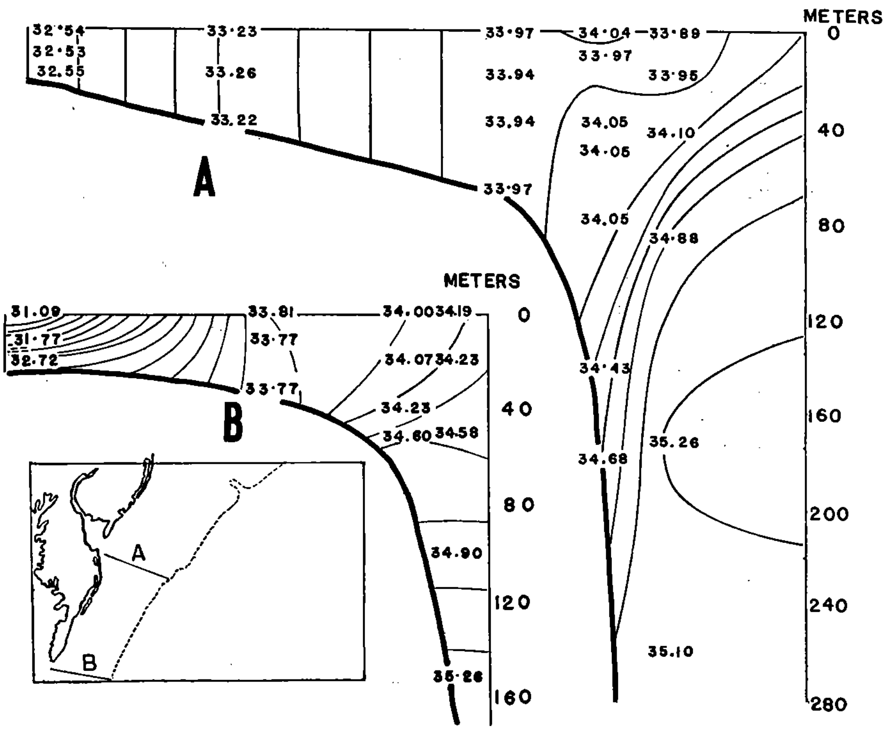


FIG. 7.—Salinity profiles crossing the continental shelf, February:—A, off Cape May, February 9, 1930; B, off Chesapeake Bay, February 10, 1930.

and the increase in salinity with depth characteristic of the lower, just described for individual stations, gives a distinctive obliquity to the isohalines as seen in profile.

The alternate and intermediate states, illustrated in Figures 6–8, show that lower values of salinity ($<34.00\ ^{\circ}/_{\circ\circ}$–$34.5\ ^{\circ}/_{\circ\circ}$) may either be spreading slightly seaward at the surface at this season (this, more or less developed, is the usual state) or may be indenting, seaward, into the more saline offshore water at some depth slightly below the surface. Among the February–March profiles to the northward of latitude 36°, none show any pronounced development of the opposite kind, i.e., encroachment landward, of high salinities in the upper strata, past the 150 meter contour. There may or may not be a definite convergence along the continental edge, in any given sector, for the abruptness of transition between shelf and slope waters varies widely from profile to profile, depending on the mutually conflicting tendencies toward offshore movement on the part

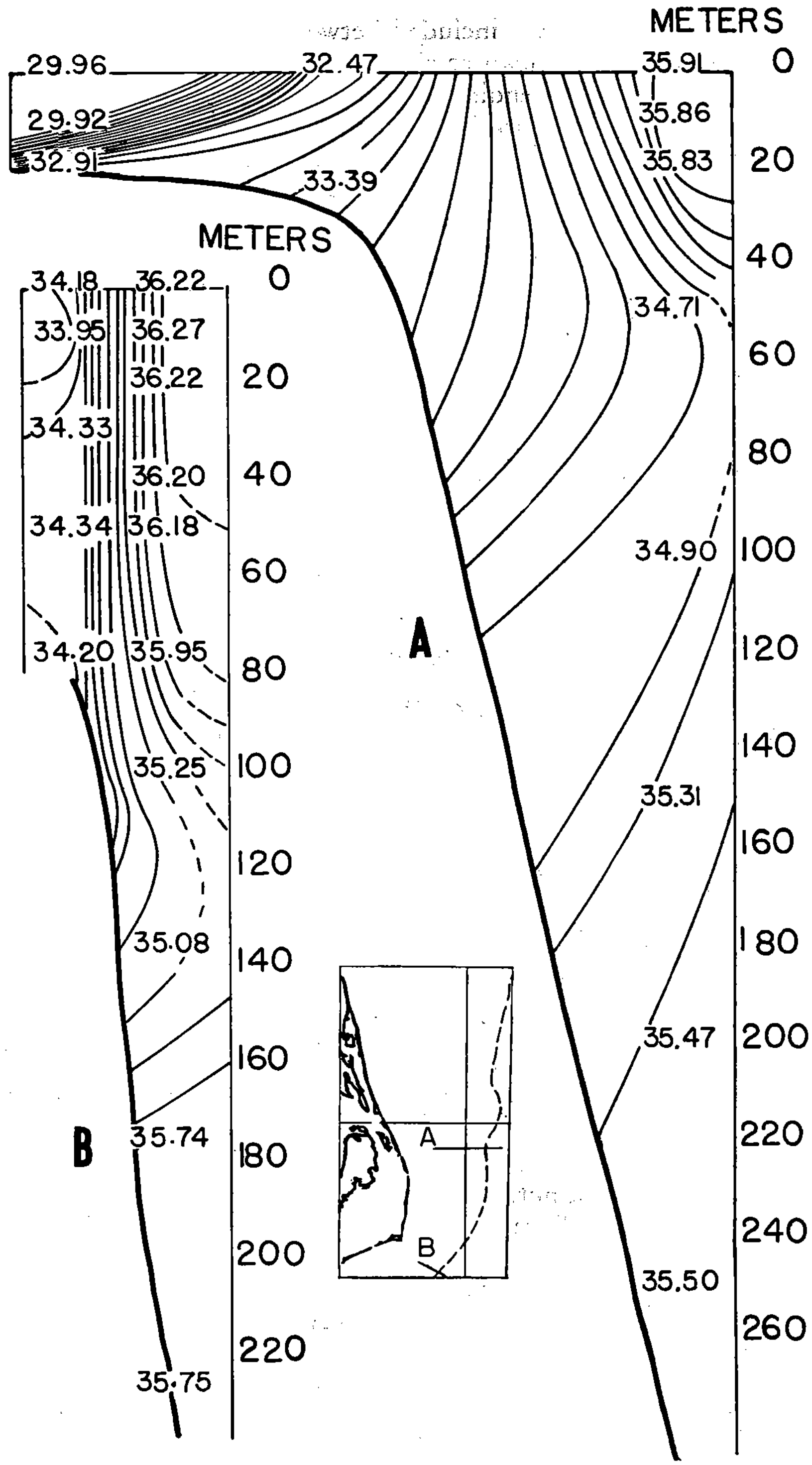


FIG. 8.—Salinity profile crossing the continental shelf:—A, off Bodie Island, February 11, 1930; B, off Cape Hatteras, February 22–23, 1931.

of the former, and toward inshore movement on the part of the latter. The most sudden transition of this sort yet recorded, for winter, is in the vicinity of Cape Hatteras—a change of nearly 2.0 °/₀₀ in a distance of 7 or 8 miles (Fig. 8 B).

Abreast of Cape Hatteras in February, 1931, the isohaline for 36 °/₀₀ was about 20 miles out from the 200 meter contour line; near latitude 36° it lay about 40 miles out from the 200 meter line in January 1914 (Bigelow, 1917 a, Figs. 2, 49). And none of the winter profiles run to the northward of Chesapeake Bay have, at any depth, reached salinities as high as 36 °/₀₀ within the area covered in the present study (Fig. 16), maximum values along the continental slope being 35.00 °/₀₀–35.6 °/₀₀ in the upper 160 meters, 34.9 °/₀₀–35.00 °/₀₀ deeper down, at this season.

*Bottom.* Bottom values may be decidedly higher than surface at such of the inshore stations as show pronounced surface freshening; for example, the bottom was about 2.95 °/₀₀ saltier than the surface off Bodie Island, in 20 meters, on February 11, 1930; 1.6 °/₀₀ saltier off the mouth of Chesapeake Bay in 22 meters, February 10, 1930; 0.95 °/₀₀ saltier close in to the coast of New Jersey (Barnegat profile), March 2, 1929, in 15 meters. And thanks to the steep vertical gradient existing in such situations at this season the lowest bottom value, even at the innermost stations, and at depths as shallow as 18 to 22 meters, is about 32 °/₀₀.

Within the zone bounded by the 18 and 30 meter contours the value close to bottom has varied between 32 °/₀₀ and 33.64 °/₀₀ (mean 32.7 °/₀₀) at our February–March stations (12 stations) between the offings of Chesapeake Bay and of New York. No bottom data are available for the inshore belt (including Long Island Sound) to the eastward of New York, until the Gulf of Maine is reached (Bigelow, 1927). But the general uniformity of distribution along the shelf suggests a mean bottom value not far from 32.5 °/₀₀, for the 20 meter line along this sector also, which is about 0.1 °/₀₀–0.2 °/₀₀ more saline than at an equal depth in the neighboring side of the Gulf of Maine. In the opposite direction, no definite north-south gradient appears along this zone, from the New York profile past Delaware Bay. But the recorded maxima and minima at 22–24 meters (32.72 °/₀₀–33.64 °/₀₀) are higher off Chesapeake Bay than on the more northerly profiles (31.99 °/₀₀–32.87 °/₀₀); increasing to about 32.9 °/₀₀–33.7 °/₀₀ (3 stations) off Bodie Island, and Currituck, and to about 33.9 °/₀₀ off Ocracoke Inlet (February 23, 1931).

Midway out on the shelf, where the bottom seldom differs from the surface by more than 0.1 °/₀₀ in salinity at this season, the bottom has ranged from 32.22 °/₀₀ to 34.38 °/₀₀ between the Martha's Vineyard and the Bodie Island profiles along the 30–45 meter belt (15 stations); from 32.8 °/₀₀ to 34.33 °/₀₀ within the 45–60 meter belt (12 stations), with mean values about equal for the two zones (33.4 °/₀₀, 33.5 °/₀₀).

The following tabulation of the gradient of bottom salinity transverse to the shelf between the 30 and 60 meter contours, southward as far as latitude 36°, shows that this is on the whole least off Martha's Vineyard to the northeast; somewhat greater off Chesapeake Bay to the south, the mean increase, from N.E. to S. (years 1929–1931 combined) being about 1 °/₀₀ in a distance of about 270 miles.

| Profiles | 1929 | 1930 | 1931 | Mean |
|---|---|---|---|---|
| Martha's Vineyard | 0.3 °/₀₀ | 0.1 °/₀₀ | 0 °/₀₀ | 0.1 °/₀₀ |
| Montauk | 0.3 | 0.8 | 0.3 | 0.5 |
| New York | 0.5 | 0.7 | — | 0.6 |
| Cape May | 0.4 | 0.7 | — | 0.55 |
| Chesapeake Bay | 0.5 | 1.2 | 0.3 | 0.7 |

Farther out, along the 60–100 meter zone, bottom salinities have varied between 32.8 °/₀₀ and 33.3 °/₀₀ off Martha's Vineyard; between 33.3 °/₀₀ and 34.2 °/₀₀ off New York; and between 34.2 °/₀₀ and 34.6 °/₀₀ off Chesapeake Bay and southward nearly to

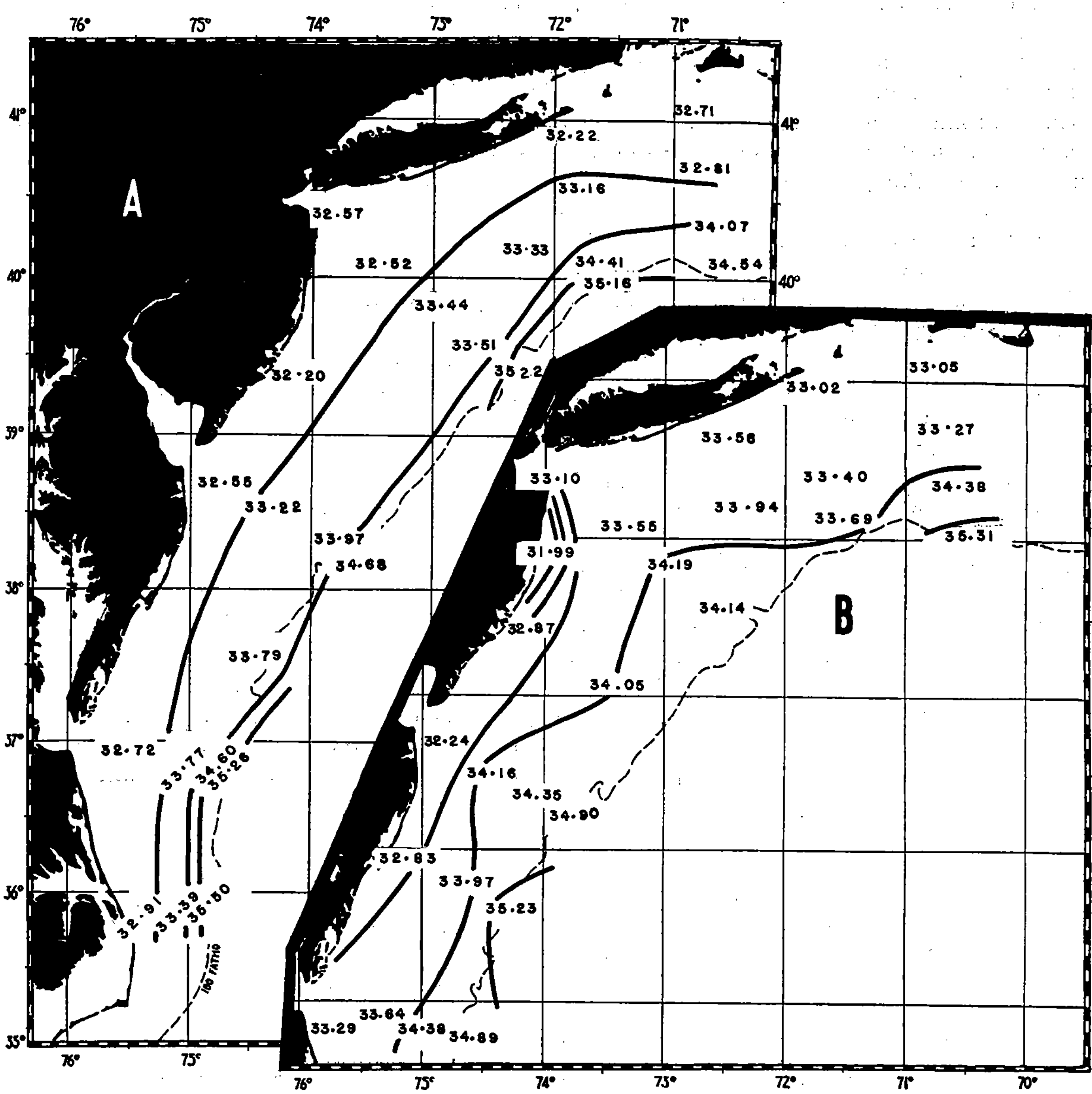


Fig. 9.—Salinity close to the bottom; out to the 200 meter contour:—A, February 5–13, 1930; B, February 24–March 5, 1929.

Cape Hatteras, which similarly shows a mean gradient, from northeast to southwest, of not far from 1 °/₀₀.

The narrowness of the long-shore gradient to the northward of Cape Hatteras contrasts on bottom (Fig. 9), as it does at the surface (p. 8, Fig. 1), with a north-south increase in salinity, over the outer part of the shelf just south of the cape of some 2 °/₀₀ in a distance of not more than 6 miles (Fig. 2 B), a transition so abrupt that it forms the most extreme convergence zone for salinity (as for temperature, Bigelow, 1933, p. 11), existing anywhere along the continental shelf of eastern North America between Tropics and Arctic.

The data farther out, along the outer margin of the shelf, are too scattering to allow any precise plotting of bottom salinities by depth zones. They show, however, that water slightly more saline than 35 °/₀₀ usually washes the bottom near the edge of the continent at least as far north as the New York profile (or farther), with its inshore boundary varying in location between the Chesapeake Bay and New York profiles from near the 110 meter contour line (Chesapeake profile, February, 1930), to the 240 meter line (Cape May profile, February, 1930); its mean location for this sector has roughly coincided with the 150–160 meter contour line.[6]

Thanks to the fact that water so saline usually touches the bottom all along the continental edge, the Cape Hatteras convergence decreases in abruptness with increasing depth below 80–100 meters. Thus the difference in salinity between the Ocracoke and Hatteras profiles, in February, 1931, which was about 2 °/₀₀ at the 80 meter level, was only about 1.1 °/₀₀ at 140 meters, and may well have been nil at 250 meters and deeper.

How far to the eastward slope water as saline as 35 °/₀₀ is in continuous contact with the bottom, at this season, is a question of biologic interest. In 1929 this was certainly the case at least as far as the Martha's Vineyard profile (Fig. 9 B). And in 1920 the "Albatross" encountered it at the continental edge off New York;[7] also on the southwest slope of Georges Bank in longitude about 68° from about the 90 meter contour downward to about 500 meters (Bigelow, 1927, Fig. 96). But its eastern limit cannot have lain much farther to the east at the time, for the highest bottom value, on the southeast slope of the bank (longitude about 66°20′), a few days later was less than 34.9 °/₀₀ (Bigelow, 1927, Fig. 97). On the other hand, 35 °/₀₀ water was not in contact with the bottom on the Montauk profile of February, 1929 and 1930,[8] and may not have been in 1931, when it did, however, wash the bottom off Martha's Vineyard.[9]

From the foregoing it appears that, in most winters, 35 °/₀₀ water touches the bottom along the upper part of the continental slope at least as far eastward as longitude 71°, and as far as longitude 68° in some years, but perhaps never more than a few miles beyond this point. In still other years, it may depart from actual contact with the bottom between longitude 72° and 71° at this season, though touching the slope in spots, farther east.

Available data, for late winter, indicate that the lower boundary of this >35 °/₀₀ bottom water lies somewhere between the 300 and 500 meter contours, all along the sector where it is in continuous contact with the sea floor:—the stations have not been spaced closely enough to show its location more precisely than this.

The maximum bottom value, at any depth, for the slope north of Cape Hatteras, is

[6] Among the February–March profiles extending out past the 150 meter line, one (Cape May, February 20, 1928) lacks readings near bottom in the outer part. Another (Bodie Island, February 17–26, 1931) failed to reach water as saline as 35 °/₀₀, out to the 180 meter line, but from the general pattern existing at the time, it seems certain that water of that salinity would have been found slightly deeper down the slope.

[7] "Albatross" station 20043, February 21, 1920; 200 M; 35.21, °/₀₀, U. S. Bureau of Fisheries, 1921.

[8] The Martha's Vineyard profile for that February was not demonstrative in this respect, for it extended seaward only to the 132 meter contour line.

[9] No Montauk profile for that February.

certainly not higher than about 35.5 ‰ at this season; the mean value of the belt with salinities above 35 ‰ is about 35.2 ‰–35.3 ‰, with no apparent north-south gradient between the offings of Martha's Vineyard and latitude about 36°.

Salinity in general agrees with temperature in the fact that the upper part of the continental slope is bathed by a band of water with values higher than inshore on the one hand, or deeper down on the other, as well as in the general location of this band, and in its constancy from year to year, and from north to south (cf. Fig. 9 with Bigelow, 1933, Figs. 11, 12). But there is no precise correspondence between the locations of the boundaries of any particular values that might be selected to define either the highly saline bottom belt, or the warm one, nor between maximum values for the two qualities of the water. Thus, in years of normal temperature, bottom temperatures for February–March have varied between about 8° and 11.6° at the localities and depths where maximum values of bottom salinity (35.1 ‰–35.5 ‰) have been recorded, rising to 12°–13° in the very warm February of 1932.[10] In this respect, salinity has proved much more stable than temperature, as was, indeed, to be expected, at the localities and depths in question.

## Vernal Progression

Alterations in salinity, during the spring, mirror the balance between events of three categories; (1) an increasing increment of water discharged from the land; (2), drifts from the northeast and east; (3), indrafts of water of high salinity from offshore. The factors controlling these categories of events are only remotely interrelated, for while the first depends upon rainfall and other climatic conditions over the neighboring lands, the third is governed by mass-movements within the sea itself. For convenience, therefore, they may be considered separately.

*Effects of river water.* In the coastal waters to the north of Cape Cod, vernal freshening of the inshore belt is the most striking event in the annual cycle of salinity, resulting by April in the development of a band of low salinity (<31.5 ‰) all along the coast from Cape Cod to the Bay of Fundy (Bigelow, 1927). To the south and west of Cape Cod, the situation is more complex, for while a similar (even more pronounced) freshening of the surface may take place at the innermost stations on profiles abreast of the mouths of the large bays, it does not so uniformly involve the intervening sectors.

Proceeding from northeast to southwest, we find little evidence of it off Martha's Vineyard where surface values by months at the innermost station have been as follows:—February (1930), 32.7 ‰; April (various dates, 1930, 1931, 1932), 32.41 ‰–32.70 ‰; May (various dates, 1929, 1930, 1931, 1932), 32.36 ‰–32.67 ‰; June (various dates, 1930, 1931, 1932), 32.05 ‰–32.38 ‰. Fifty to sixty miles farther west, however (Montauk profile), where effects of spring freshets from the Connecticut river are to be expected, a decided decrease has been recorded from February to April, with surface values continuing as low or lower through May. Thus, the surface reading at this station for 1929, dropped from 32.79 ‰ on February 27, to 31.29 ‰ on April 24, and to 30.77 ‰ on May 11: in 1930, it was 32.21 ‰ on February 7; 31.82 ‰ on May 14; in 1931, 31.14 ‰ on May 16; and in 1932, 30.99 ‰ on May 15, 31.58 ‰ on the 20th, and 31.96 ‰ on the 27th (Fig. 10 D), a mean freshening by about 2 ‰ between the last half of February and the middle of May.

[10] Unfortunately no bottom salinities were taken on that cruise.

The change is (by present data) equally pronounced to the westward along the coast of Long Island in some years, less so in others, as appears from a decrease from 33.51 °/₀₀ on February 27 to 32.38 °/₀₀ on April 23 and 31.09 °/₀₀ on May 11, of 1929,[11] contrasted with mid-May and early June values (32.41 °/₀₀, 32.13 °/₀₀ for 1930) that were little if any below the probable February value.

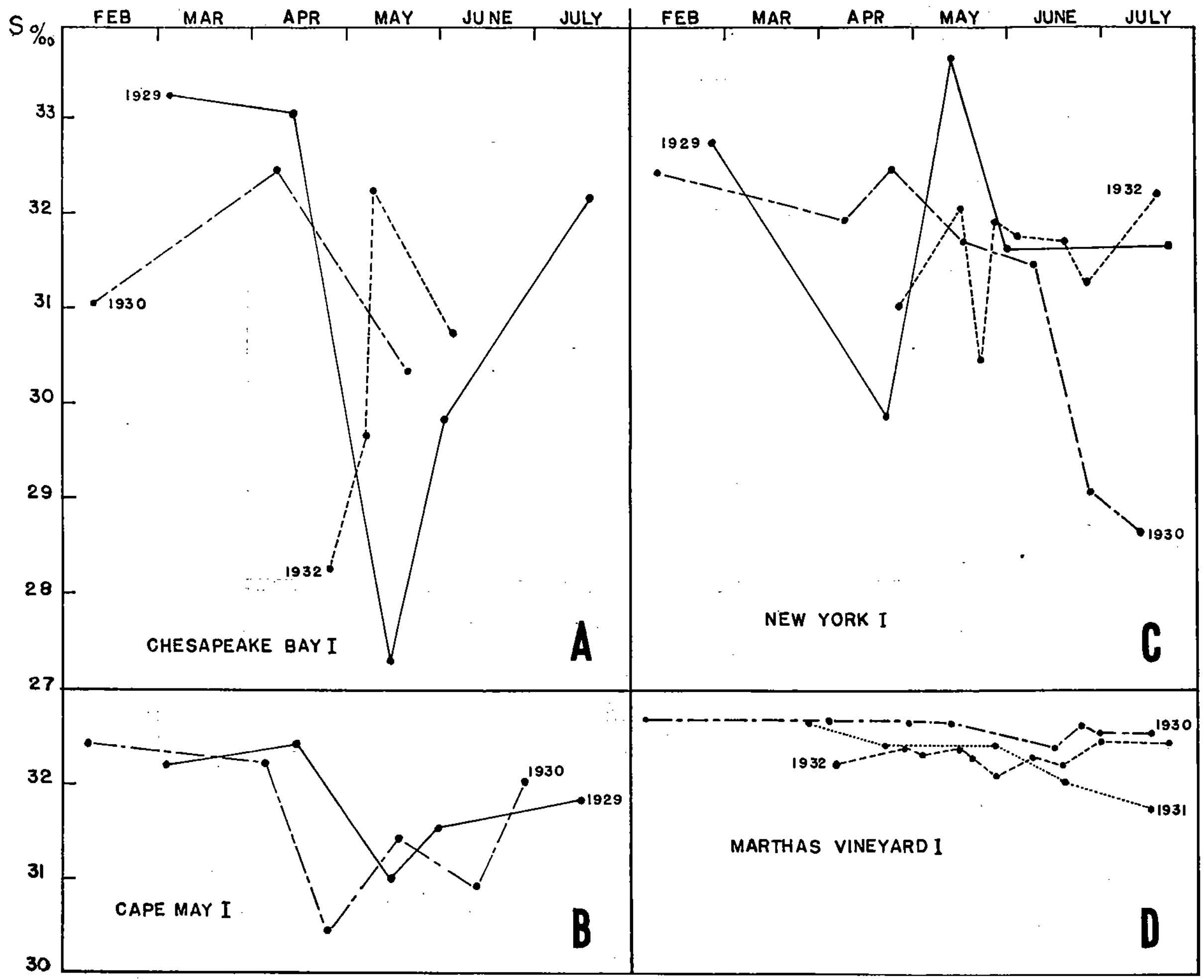


FIG. 10.—Salinity at the surface, at successive dates, in different years, at stations closest to shore: A, off Chesapeake Bay; B, off Cape May; C, off New York; D, off Martha's Vineyard.

Adequately to trace the normal seasonal succession off New York would require data much more closely spaced than are yet available, for the location of the innermost station on that profile in relation to the discharge from the Hudson river is such that wide variations in surface salinity are to be expected there, only a few miles apart; or even at the same location at different stages of the tide. The funnel-like form of the coast line may also be expected to emphasize the effects of onshore and offshore winds there, as

[11] Station Shinnecock I.

these either sweep the surface water inshore or cause upwellings. For example, the considerably higher value (33.6 °/₀₀) recorded close in to New York harbor, on May 12, 1929, than at a station 15 miles farther out (32.3 °/₀₀), was probably due to some such overturning—whether by tide or by wind. Successive observations for this general location, for individual years (Fig. 10 C) do, in fact, show fluctuations so abrupt, and so extreme, that they are most reasonably interpreted as due to local factors of these sorts, illustrating the danger of basing generalizations on scattered observations for localities of this nature. Especially striking in this respect is the contrast between the abrupt alternations between high and low values in 1929 and 1932, and the more nearly continuous freshening recorded there in 1930, for there was no corresponding difference in the seasonal fluctuation in the rate of discharge from the Hudson River in those years.

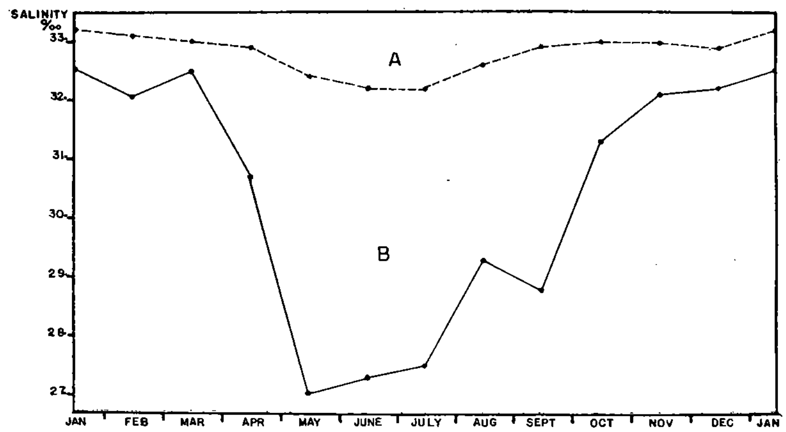


FIG. 11.—A, Mean surface salinity on line New York-Nantucket Lightship, by months, all years; B, Minimum salinity by months, all years, off New York, from steamship data.

These irregularities are, however, not sufficient to hide the underlying fact that much lower values were recorded near New York, either in April (as in 1929) or in May and June (as in 1930) than in February of the two years when observations were taken there in winter as well as in spring. Salinities were also much lower there at some time during the spring of 1927, 1928, 1931 and 1932 than is ever likely to be the case at the end of the winter (then usually 32.00 °/₀₀–32.7 °/₀₀). Mean values for this general vicinity over a period of years, have similarly shown a very abrupt decrease, from March to May. Average values along the line New York-Nantucket Lightship (in which the yearly fluctuations are smoothed out) also show a slow but unbroken decline, from January (33.2 °/₀₀) to April (32.9 °/₀₀) followed by a more abrupt freshening to June (32.2 °/₀₀) as normally characteristic of this easterly sector as a whole (Fig. 11). This corresponds to (and no doubt results from) the great increase that normally takes place in the rates of discharge from the Hudson and Connecticut rivers from February to April, followed by a correspondingly abrupt decrease (Fig. 12).

No doubt a similar explanation holds for such freshening as is recorded at the inner end of the Atlantic City profile[12] where the data for 1929 show a regular succession, from highest value at the beginning of March to lowest in mid-April, followed by a rapid re-

[12] Representative of the straight coast line between New York and Delaware Bay, along which no great amount of land water enters the sea.

covery through May, though (for some reason) freshenings alternated irregularly with saltings in 1930 and 1932. Off the mouth of Delaware Bay, where alterations in surface salinity are seemingly more regular, vernal freshening reaches its climax about a month after the discharge from the Delaware river passes its peak (cf. Fig. 10 B with Fig. 12), though differences in the geographic locations of the stations makes it impossible to state the exact amount by which salinity decreased in either year of record (1929, 1930).[13]

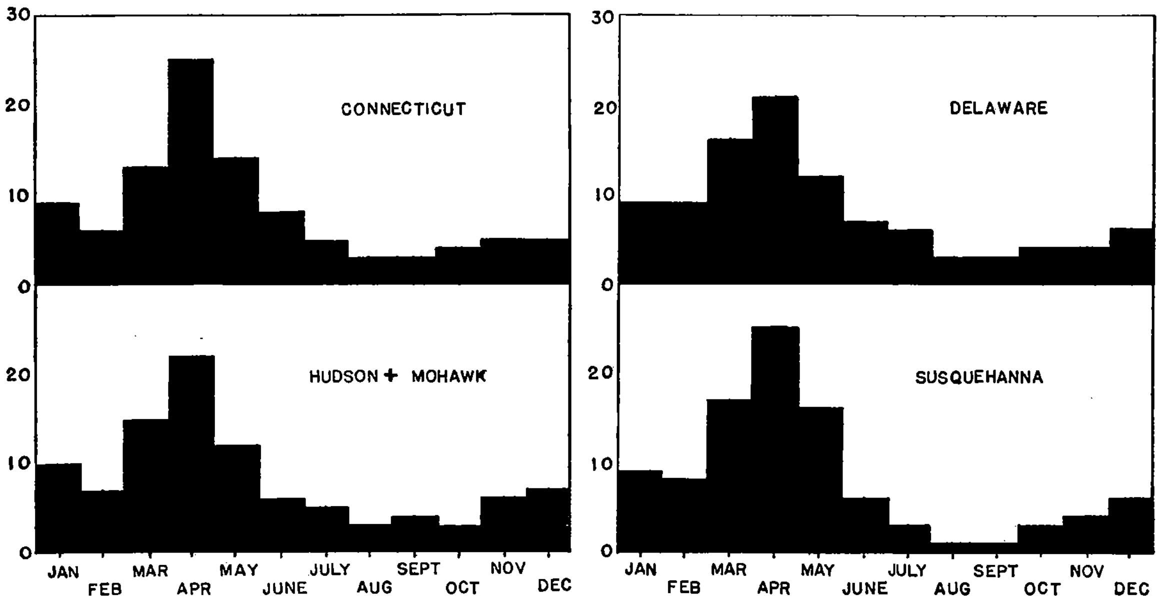


FIG. 12.—Mean monthly percentages of total annual discharge for the years October, 1928–September, 1932, for the Connecticut, Hudson and Mohawk, Delaware and Susquehanna rivers. The data (U. S. Geol. Survey 1931–1934) are for the gaging stations nearest the river mouths, covering 86%, 90±%, 97% and 95% respectively of the regional water sheds.

Probably this lag is due to mixing processes in the upper part of Delaware Bay, for the following surface readings at stations close to the two headlands of the latter, and a few miles out (McCries Shoal),[14] show the minima as falling as late in the season there as at our innermost station on the Cape May profile, or even later.

| | | | |
|---|---|---|---|
| 1929: | (1) | 3 miles N. to NE. of Cape Henlopen | |
| | | May 29, surface salinity | *24.58* |
| | | June 5, " " | 27.32 |
| | | June 19, " " | 27.95 |
| | | June 26, " " | 29.34 |
| | (2) | Cape May Channel | |
| | | May 29, surface salinity | 29.19 |
| | | June 13, " " | *26.56* |
| | | June 19, " " | 30.05 |
| | | June 26, " " | 30.35 |
| | (3) | McCries Shoal | |
| | | May 27, surface salinity | *31.51* |
| | | June 4, " " | 32.07 |
| | | June 11, " " | 32.45 |
| | | June 17, " " | 31.60 |
| | | June 24, " " | 31.53 |

| | | | |
|---|---|---|---|
| 1931: | (1) | 3 miles N. to NE. of Cape Henlopen | |
| | | Feb. 20, surface salinity | 30.86 |
| | | Mar. 21, " " | 30.91 |
| | | Apr. 21, " " | 28.87 |
| | | May 1, " " | 29.65 |
| | | May 24, " " | *26.26* |
| | | June 15, " " | 28.44 |
| | | June 30, " " | 30.53 |
| | (2) | McCries shoal | |
| | | Feb. 16, surface salinity | 32.30 |
| | | Mar. 19, " " | 31.60 |
| | | Apr. 30, " " | *31.08* |
| | | May 14, " " | 31.65 |
| | | June 12, " " | 31.27 |
| | | June 27, " " | 31.51 |

[13] Data for 1931 are not demonstrative for this locality, for while the May readings for that year were only slightly lower than for April, the interval between was so long that decline and recovery may have taken place in the interim.

[14] Data supplied by A. E. Parr (p. 3).

Off the mouth of Chesapeake Bay, even more than off New York, deduction from scattered observations is apt to be misleading because of the wide difference in salinity to be expected running out from the mouth of the bay, between neighboring localities. On April 23, 1932, for example, the surface reading rose from 28.24 ‰ close in, to 32.47 ‰ in a distance of only 7 miles. It seems clear, however, that, in 1929, a much more pronounced freshening of the surface took place in that general region (10 miles out from Cape Charles) from April to May, than has been recorded anywhere else along the open coast within the sector under study, followed by almost equally rapid recovery through June and July (Fig. 10, A),[15] the succession being similar, both off Hog Island, 30 miles to the northward, and off Bodie Island, 60 miles to the southward, though with the range of variation smaller, as follows:—

| | | April 18 | May 15–16 |
|---|---|---|---|
| 1929: | Sta. Hog. Island I | 33.09 | 31.67 |
| | Sta. Bodie Island I | 32.63 | 30.90 |

The foregoing schedule for that particular year corresponds well with the very abrupt seasonal increase and decrease in the discharge from the Susquehanna River, the largest river draining into Chesapeake Bay (Fig. 12), the lag between the date of maximum river flow, and of minimum salinity off the mouth of the bay, being about one month here, as it also is off Delaware Bay. It is not possible to draw so close a correlation between river flow and salinity at sea for the two other years of record (1930, 1932) when the river flow was not as large as in 1929 (U. S. Geol. Survey, 1933, 1934), for in the one case (1930), an increasing salinity, from February through April contrasts with a comparatively uniform and (for the season) large river flow, while in the other (1932), the variations in river flow afford no explanation for the abrupt, but short recovery of salinity in late April and early May, after an even more abrupt decline (Fig. 10 A). In spite of these complexities it is, however, clear that the surface just off the bay normally suffers a very marked freshening caused by the tremendous rush of water that pours into the bay during March, April, and May.

Available data do not allow the seasonal comparison to be carried farther south than this.

So far as present data go, the minimum values to be expected between February and the end of May, say, 10 miles out from the land, on the several profiles are roughly as follows: Martha's Vineyard, 31.9 ‰; Montauk, 30.8 ‰; New York, about 27.00 ‰; Atlantic City, 30.3 ‰; Cape May, 30.5 ‰; coast of Virginia, 31.3 ‰; Chesapeake Bay, about 27.3 ‰; Bodie Island, 30.00 ‰. As a result of these local freshenings the salinity is reduced below 32 ‰ at some time during the spring, all along the coastwise belt to the west of longitude about 71°30′. In the year 1929, this condition had developed from the Montauk to the Atlantic City profile by the third week of April and also close in to the coast south of Chesapeake Bay, but with the intervening coast-wise sector still continuing >32 ‰, as it had been in February (Fig. 1 C). By the middle of that May (Fig. 13 B) water less saline than 32 ‰ had expanded, to skirt the whole coast, westward and southward from the entrance of Long Island Sound nearly to Cape Hatteras, interrupted only by local pools of higher salinity off the mouth of New York harbor, and off Winterquarter which were probably the result of local overturnings. And so far as the data go, the seasonal schedule seems to have been approximately the same in 1931, when water <32 ‰ bordered the coast, from the Montauk to the Winterquarter

[15] The geographic localities of these readings all lay close together.

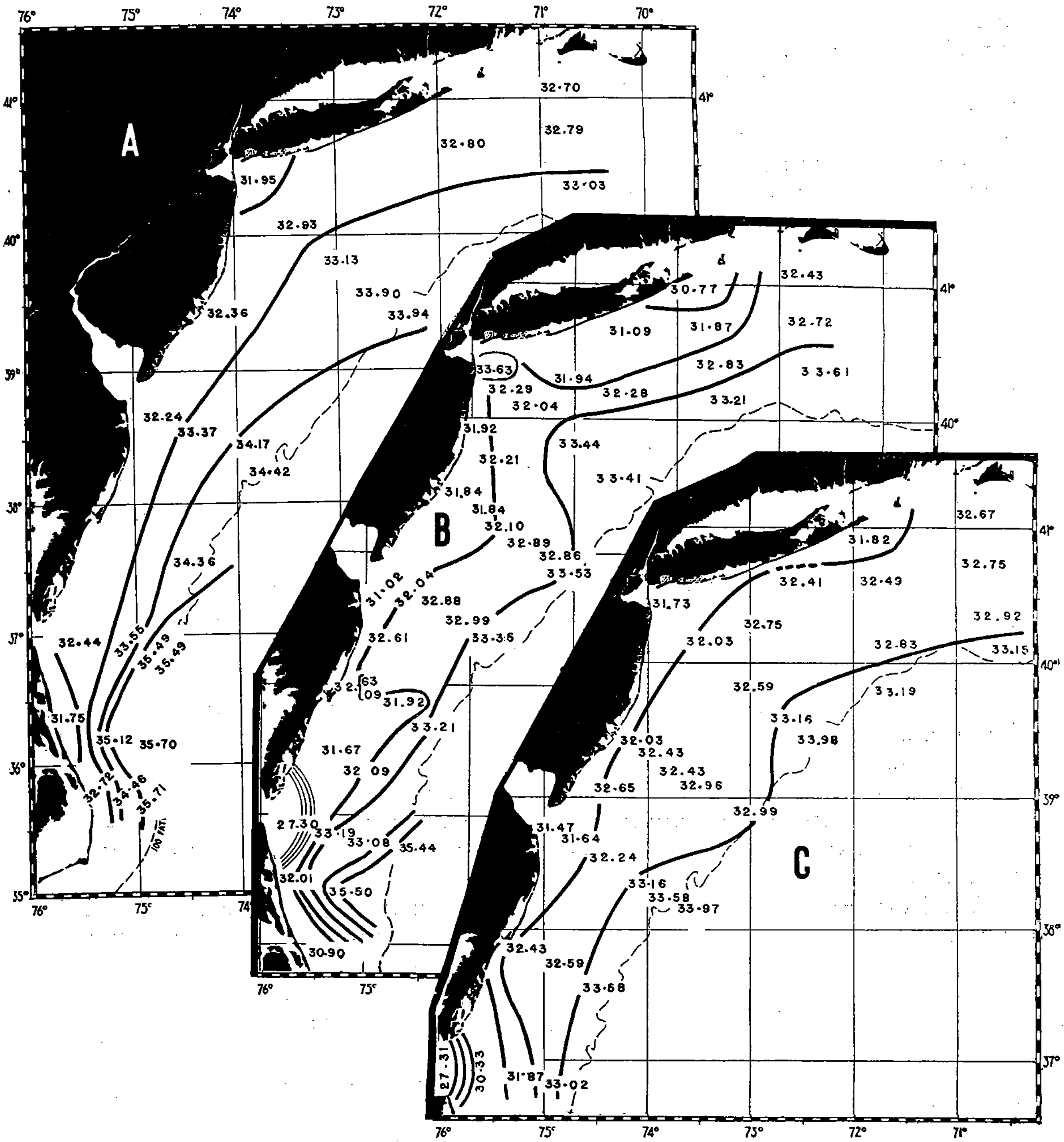


FIG. 13.—Salinity at the surface in April and May:—A, April 3–11, 1930; B, May 10–18, 1929; C, May 12–23, 1930.

profile[16] on May 16–22; broadest (about 60 miles) off New York, and interrupted only at the mouth of Delaware Bay by a local pool of slightly higher value (32.26 $^{\circ}/_{\circ\circ}$). In 1930 and 1932 the development was more tardy, for in the latter year <32 $^{\circ}/_{\circ\circ}$ water did not spread along the coast as a whole between Montauk and Delaware Bay until the third week of May, and even then, still continued interrupted between the latter and Chesapeake Bay, while in 1930, it was confined to the vicinities of sources of discharge of river water until well into June.

None of the spring cruises have shown water less saline than 31 $^{\circ}/_{\circ\circ}$ as occupying anything more than small pools, close to the regions of discharge, the most extensive being recorded for 1929, when values less than 31 $^{\circ}/_{\circ\circ}$ extended from New York southward along the coast for some 75 miles in April (to be absorbed shortly thereafter), and when the effects of the discharge from the Chesapeake, appeared by the first of June as an expansion <31 $^{\circ}/_{\circ\circ}$ midway out across the shelf, and northward, along shore, for some 50 miles.

On the regular cruises, values lower than 30 $^{\circ}/_{\circ\circ}$ have been recorded only at the innermost station off New York (April 21, 1929, 29.84 $^{\circ}/_{\circ\circ}$; June 26, 1930, 29.09 $^{\circ}/_{\circ\circ}$; July 12, 1930, 28.68 $^{\circ}/_{\circ\circ}$); at the mouth of Chesapeake Bay (April 23, 1932, 28.24 $^{\circ}/_{\circ\circ}$; May 14, 1929, 27.30 $^{\circ}/_{\circ\circ}$; June 1, 1929, 29.81 $^{\circ}/_{\circ\circ}$; May 19, 1930, 27.31 $^{\circ}/_{\circ\circ}$); and close to land a few miles to the north (Hog Island, June 1, 1929, 29.31 $^{\circ}/_{\circ\circ}$). The steamship data near New York (p. 3) also include a number of very low readings (27.00–29.00 $^{\circ}/_{\circ\circ}$) between May and September 1928.

As the season advances the effect of the vernal outflow of land water appears, not as a further decrease in surface salinity near shore, but as a progressive expansion of the zone within which surface values have decreased appreciably below their winter level. In the two years (1929, 1930) when general surveys were made in April–May as well as in February, the isohaline for 33 $^{\circ}/_{\circ\circ}$ which lay close inshore in February (Fig. 1 B, C) and in April (Fig. 13 A), had shifted well out on the shelf by mid-May and was near the continental edge in June (Fig. 14). This may be taken as normal, for the situation was much the same in 1931 and 1932. But it is evident that wide variations may be expected in individual years, for late May of 1927 showed a much wider expansion of <33 $^{\circ}/_{\circ\circ}$ water, to well outside the continental edge, whereas in the same month of 1928, the isohaline for that value lay considerably farther in on the shelf than in any other May of record.

The locations of individual isohalines, especially that for 32 $^{\circ}/_{\circ\circ}$ (Fig. 15) yield the only available information as to the routes of dispersal of water of low salinity from its chief sources. On this basis it seems clear that the outflow from Long Island Sound (carrying the voluminous discharge from the Connecticut and Hoosatonic Rivers) has very little effect to the eastward, but that it spreads offshore, and to the westward. The Hudson River (New York harbor) influence seems in 1928, 1929 and in 1932 to have been diverted chiefly southward alongshore, whereas it seems to have spread farther offshore in 1930 and 1931.

The fact that surface charts of salinity less definitely outline the outflow from Delaware Bay is due, at least in part, to active mixing within the funnel-shaped bay, itself. The tendency for higher surface values to persist just to the south of the mouth of the bay contrasts with the distribution along a line crossing the latter from headland to

[16] No data farther south.

headland, where Parr's data show transition from lower values next the southern side, to higher next the northern, as follows:—

1929: May 27–29; near C. Henlopen, 24.58 °/₀₀; near Cape May, 29.18 °/₀₀.
June 17–19; near C. Henlopen, 27.95 °/₀₀; near Cape May, 30.05 °/₀₀.

None of the cruises gave evidence of any pronounced fan of low salinity abreast of Delaware Bay. A phenomenon of this sort did, however, develop off Chesapeake Bay,

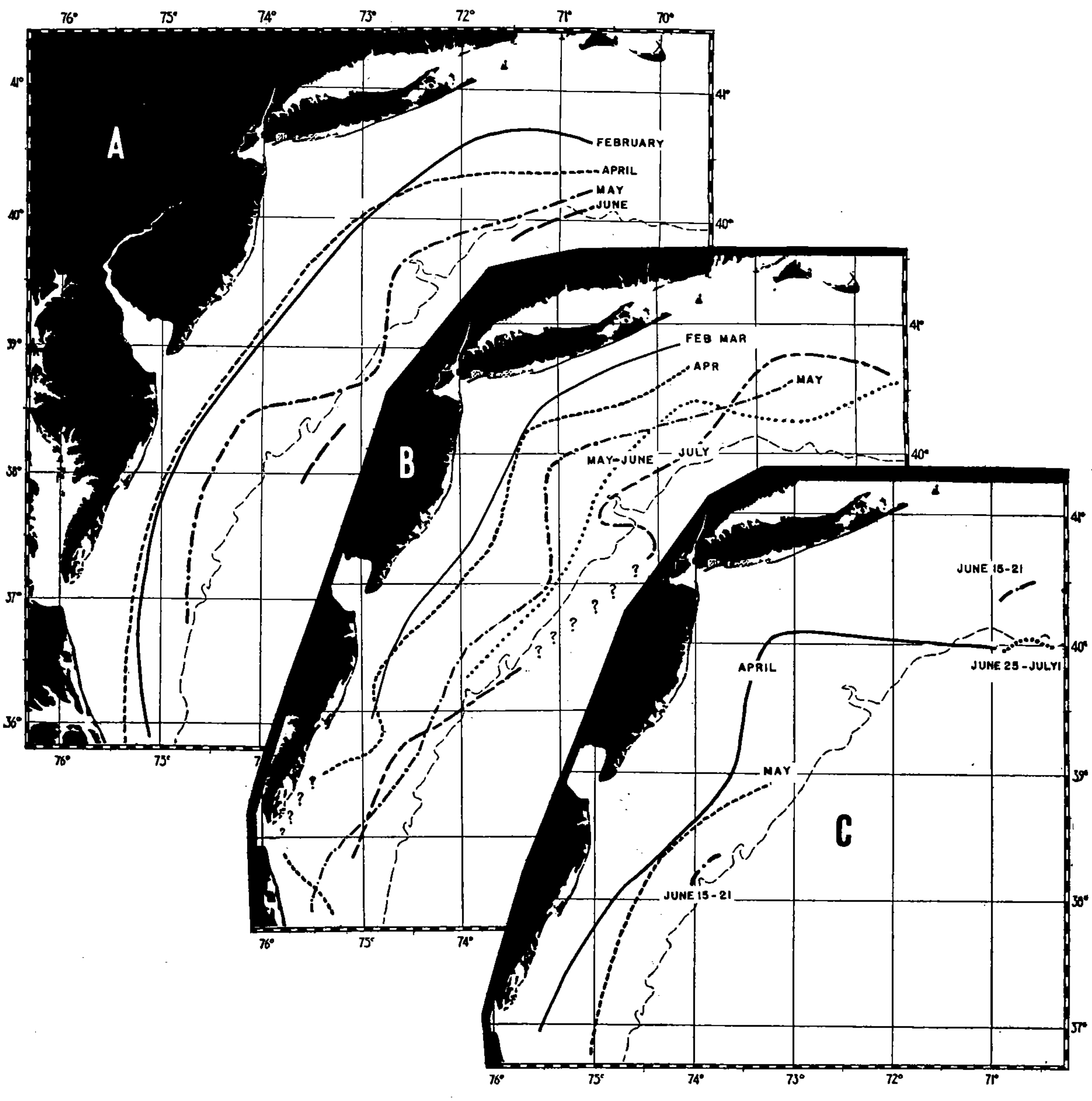


FIG. 14.—Location at the surface of the isohaline for 33 °/₀₀ in successive months:—A, 1930; B, 1929; C, 1932.

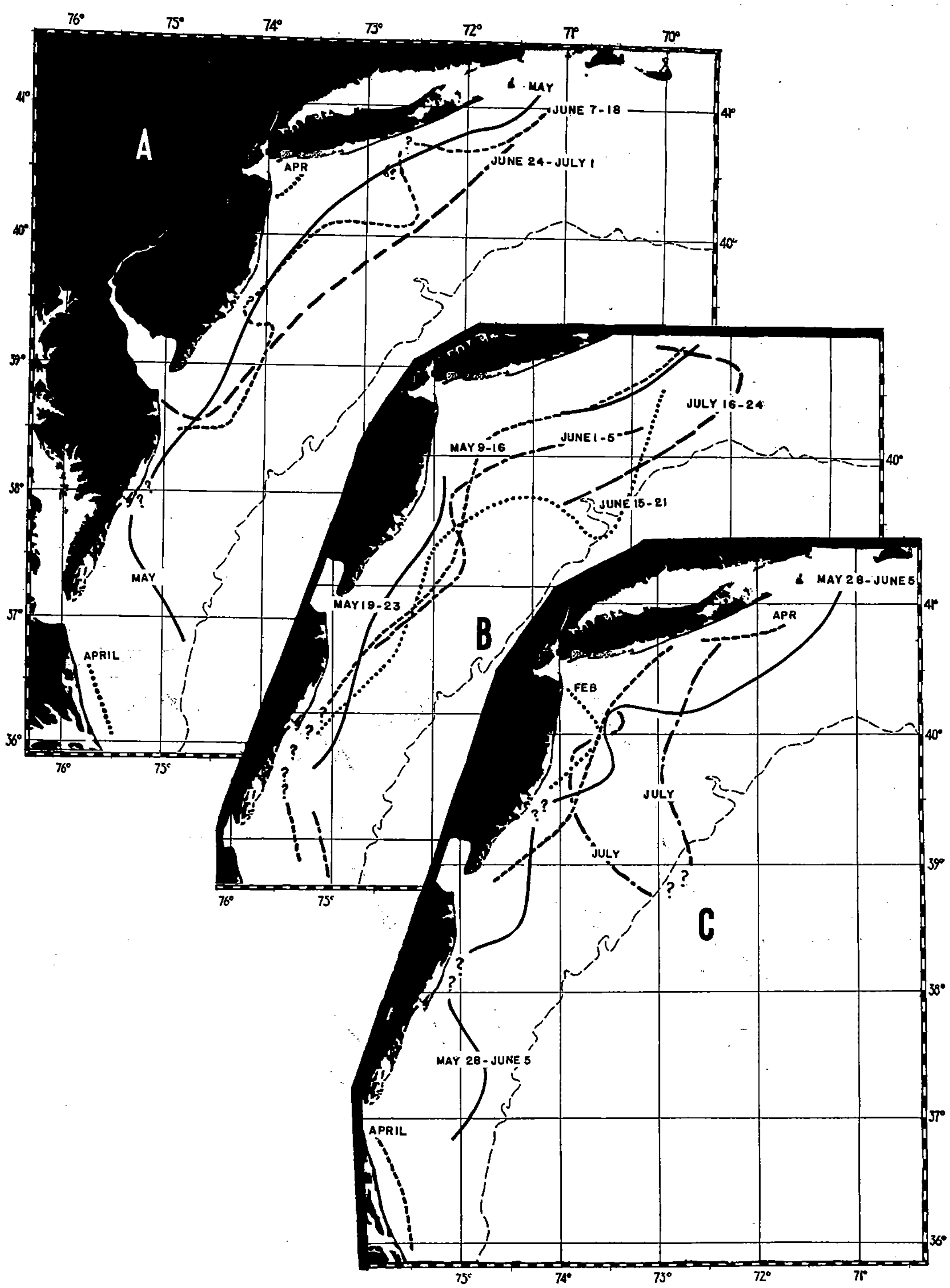


FIG. 15.—Location at the surface of the isohaline for 32 °/₀₀ at successive dates:—A, 1930; B, 1932; C, 1929.

during the last half of May in 1929 (cf. Fig. 15 with Fig. 14 B); also between early April and mid-May in 1930; whether or not in 1931 or 1932 the data do not show. On the other hand, we have no clear evidence of any great spread of Chesapeake Bay water southward, alongshore, for while values below 31 °/₀₀ were recorded near the coast line off Bodie Island on May 15, 1929, as well as on February 11, 1930 (30.90 °/₀₀ and

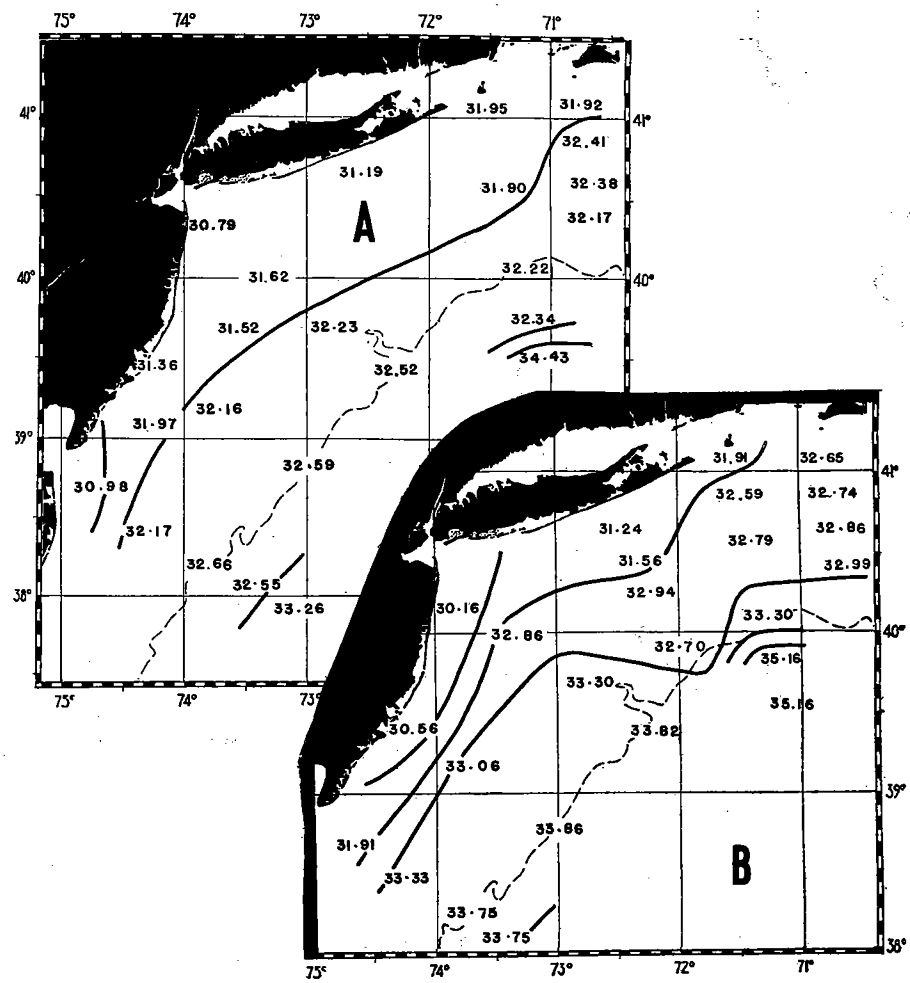


FIG. 16.—Salinity at the surface:—A, May 18–28, 1927; B, May 22–30, 1928.

29.96 °/₀₀, respectively), this was so close to an inlet that local outflow from Albemarle Sound may have been responsible.

If the mid-May cruises of 1927, 1928 (Fig. 16), 1929, 1930, 1931 and 1932 (Fig. 17) may be taken as representative of extreme, and median conditions to be expected along different sectors of the coast at that season, from year to year (though not necessarily synchronously all along the shelf in any one year) it seems that surface water <32 °/₀₀ may, on the one hand, be confined to isolated pools next the coast off Montauk, from

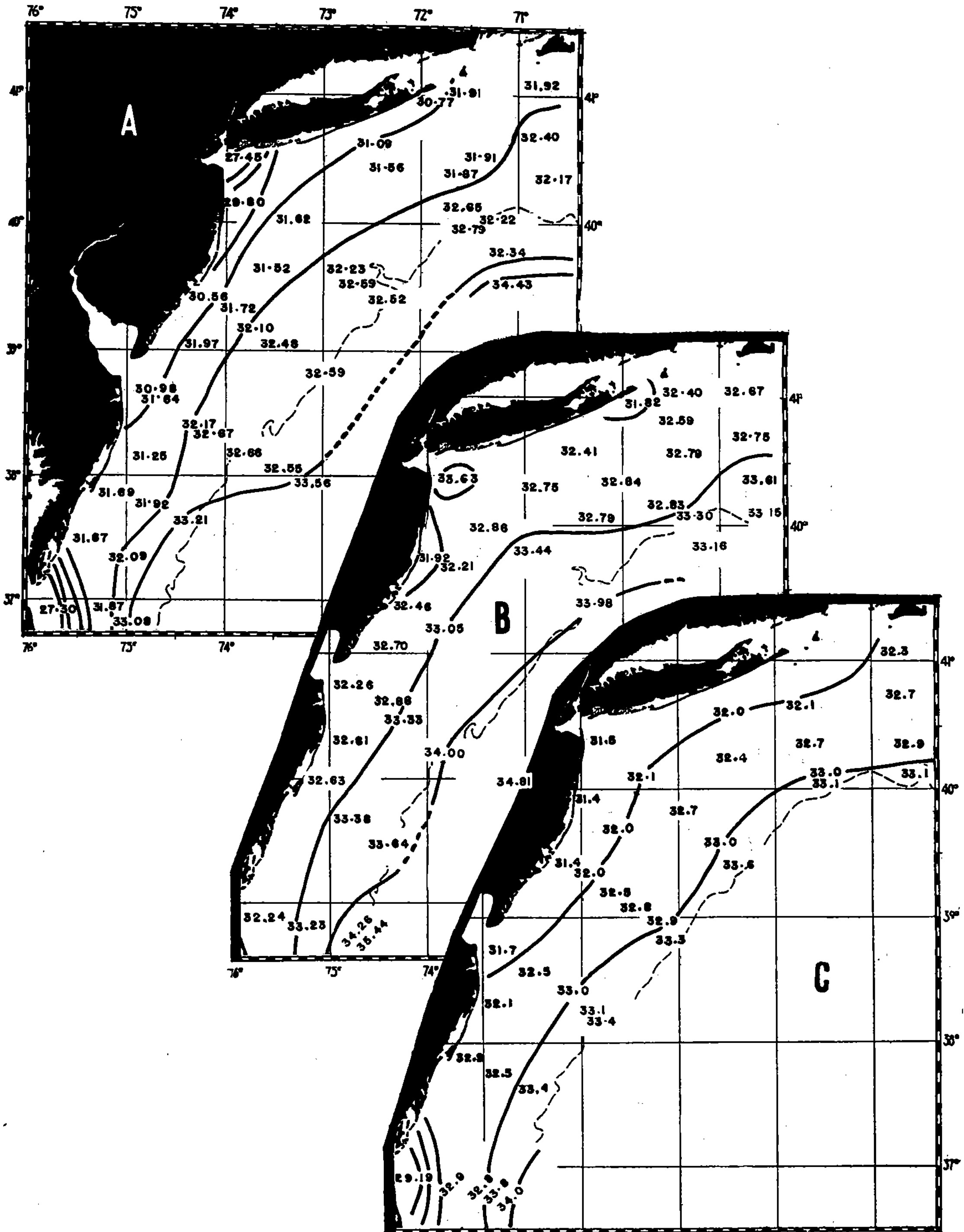

FIG. 17.—A, minimum; B, maximum; and C, mean values of salinity at the surface, for May, of the several years, combined.

New York southward past Delaware Bay, and near the mouth of Chesapeake Bay, or (at the other extreme) water of this low salinity may occupy a continuous belt, varying in width from 30–50 miles in the northern half of the area, to 25–30 miles in the southern (Fig. 17 A, B). Similarly the inner boundary of water more saline than 33 °/₀₀ may be some few miles out beyond the continental edge in a May of low salinity, or well in on the shelf in a May of high salinity. At this season, surface water as saline as 34 °/₀₀ overflows the continental edge only in years of the latter type, and this only along short sectors (Fig. 17 B). These charts also show—whether for minimal, for maximal, or for mean values—that the isohalines for mid-May parallel the general coastal trend with regularity that seems surprising in view of the regional irregularities already outlined; nor do they outline the river discharges at all, except for that off Chesapeake Bay. Thus they corroborate the evidence set forth above (p. 25) that when surface tongues of low salinity do develop, they are short-lived.

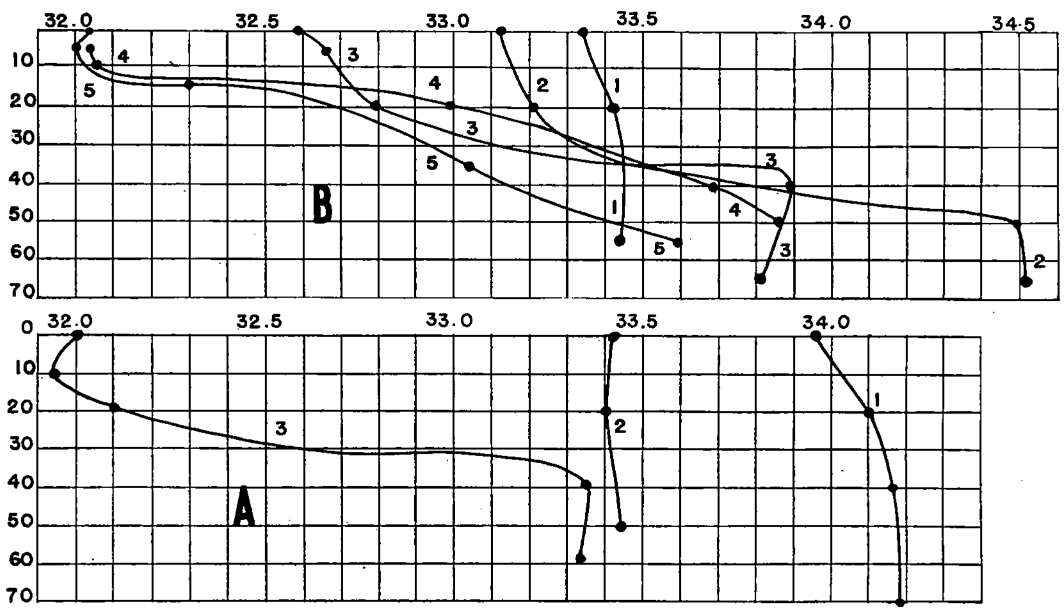


FIG. 18.—Vertical distribution of salinity on successive dates at station New York III:—A, 1929; (1) February 28; (2) April 21; (3) July 22. B, 1930; (1) February 7; (2) April 11; (3) May 16; (4) June 26; (5) July 12.

The effects of vernal freshenings, by land water, decrease rapidly with depth, as is of course to be expected. And the task of tracing their quantitative effects is made increasingly difficult, as depth increases, by the increasing conflict with indrafts of highly saline water over the bottom from offshore, discussed below (p. 30). In years when the latter are weak throughout the area as a whole (as in 1929), or along sectors but little affected by them, surface freshenings are accompanied, or followed at some time during the spring, by a decided decline in salinity, throughout the whole column, from the coast line right out across the shelf to the 70–80 meter contour line. In 1929, for example, the whole column of water, surface to bottom, was considerably less saline at all the stations out to that depth (Stations I–III of each profile) in April than in February–March (Fig. 18), except at the mouth of Delaware Bay (Station Cape May I), where surface freshening at the surface did not gather head until later in the season,

(Fig. 10 B) and on the Montauk profile, where a salty indraft from offshore produced the opposite effect in the bottom stratum, on the outer part of the shelf. With these exceptions, bottom values, for that particular year, ranged from 0.3 °/₀₀ to 1.00 °/₀₀ lower in April than at the end of February, from the coast right out to the 70–80 meter contour, and with but little gradation in this respect, transverse to the shelf.

It is unfortunate that the observations for 1929 did not extend eastward as far as the Martha's Vineyard profile, because the latter contrasts so strongly with the waters farther west in showing little sign of vernal freshenings at the surface. However, the profiles for 1930, 1931 and 1932 show that the subsurface strata experience no more definite periods of vernal freshening there, than does the surface (p. 18), whether inshore, or midway out on the shelf (Fig. 19). On the contrary, the most notable events in the deep layers there, in spring, are brief indrafts of high salinity at the bottom, followed by periods during which salinity again decreases as this offshore water is incorporated.

*Effects of drifts from the east.* Surface drifts from the east, which are so important an event in the vernal progression of temperature, would not tend much to alter the values of salinity as previously existing, unless the latter had recently been increased by indrafts of slope water. But had such an indraft recently occurred, any drift of coastal water from the east would tend to counteract its effect.

From the standpoint of temperature, the most striking drift of this sort that has come under direct observation took place in the early spring of 1930, when the upper strata off Martha's Vineyard chilled by 2°–5° between February 5th and April 3rd, instead of warming according to the seasonal expectation. Even in this case, however, salinity would not, by itself have revealed any such drift, for while a slight freshening of the upper 40 meters did take place (contrasting with a salting of the bottom water) this might equally have been interpreted as resulting from the general freshening normal to the season, had not the evidence of temperature been available. And this applies equally to the other instances of cold drifts recorded elsewhere for April and May, of the years 1927, 1929 and 1932 (Bigelow, 1933, pp. 30, 38).

In the deeper strata, along the upper part of the continental slope, drifts from the east may cause an increase in salinity, by adding to the volume of >35 °/₀₀ water, as discussed below.

*Effects of indrafts of slope water.* While changes in salinity do not identify drifts of cold water from the east, they are excellent keys to movements of slope water in over the shelf, there being no other source for high salinities in this region.

As previously described (Bigelow, 1933, p. 31), a widespread encroachment of this sort took place to the westward of longitude 72°, and southward, between February and early April of 1930. How great a volume of water was involved is illustrated in a striking way, by the New York profile (Figs. 1, 9 B, 20), where 34 °/₀₀ water had crept in, over the bottom to the 50 meter contour, i.e., to within some 40 miles of the coast, a shift in position of about 30 miles. As this synchronized with some expansion of values lower than 33 °/₀₀ at the surface, it caused the development of a strong vertical gradient over the shelf as a whole, accompanied either by a loosening of the zone of convergence that existed near the edge of the continent earlier in the season, or a shift in the position of the latter so far offshore that the profile did not reach it. During the same interval, and from the same cause, the Cape May and the Chesapeake Bay profiles showed a similar steepening of the vertical gradient, especially over the inner part of

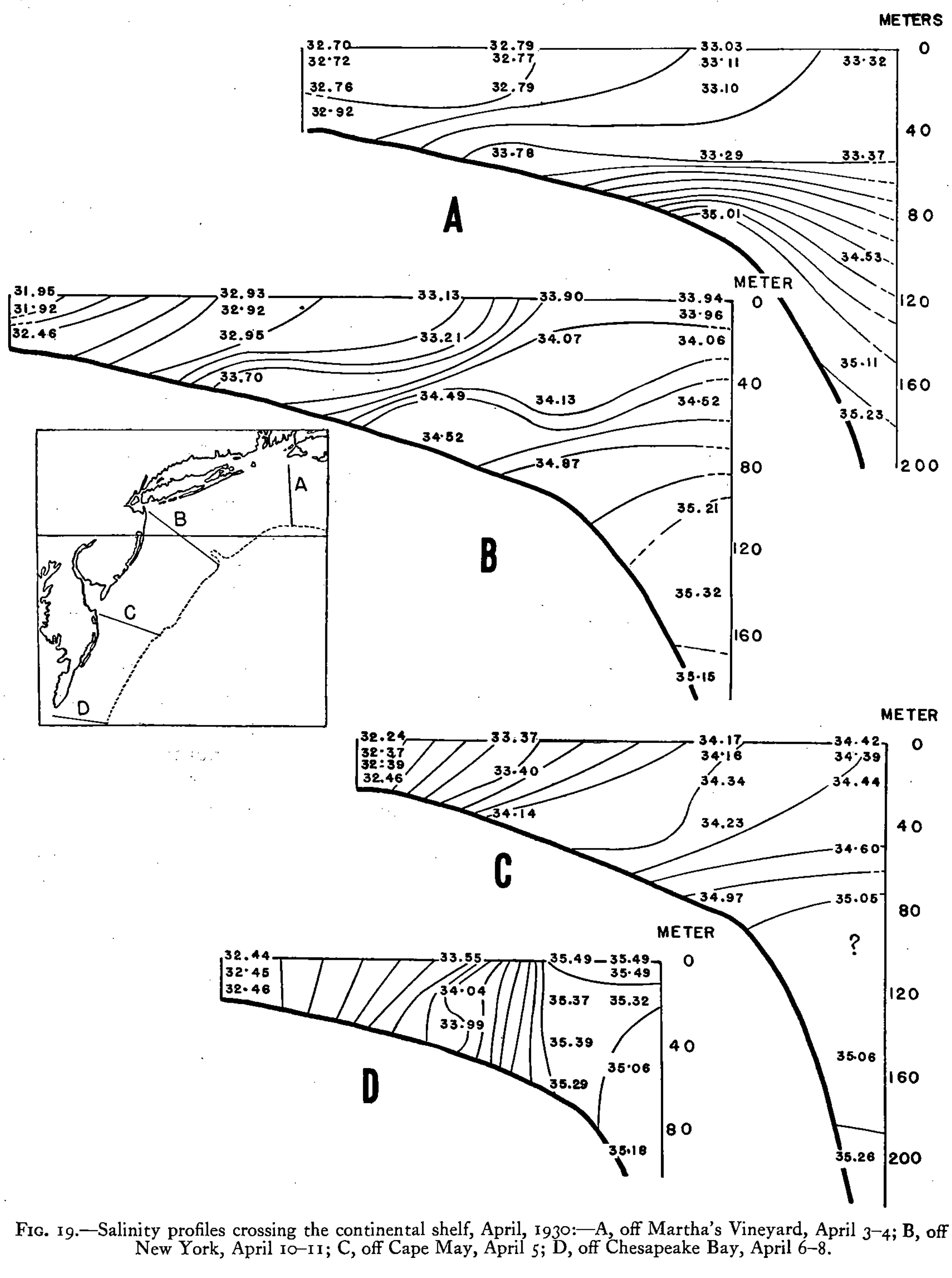


FIG. 19.—Salinity profiles crossing the continental shelf, April, 1930:—A, off Martha's Vineyard, April 3–4; B, off New York, April 10–11; C, off Cape May, April 5; D, off Chesapeake Bay, April 6–8.

the shelf; in the latter case, water more saline even than $35\ ^{\circ}/_{\circ\circ}$ had come to occupy the whole water-column as far in as the 50–60 meter contour, by April. And this encroachment no doubt extended south to Cape Hatteras, for the sequence of events was much the same off Bodie Island, in that spring as off Chesapeake Bay (cf. Fig. 7 B with Fig. 19 D).

In that particular year, the supply of slope water seems then to have diminished, for the isohaline of $34.5\ ^{\circ}/_{\circ\circ}$ receded again to the outer zone of the slope, with $35\ ^{\circ}/_{\circ\circ}$ water, contracting once more to the edge of the continent, i.e., to about its February position (cf. Figs. 27 A with 27 B).

Some encroachment, of the same sort, also took place from latitude about 37°30′ northward at about the same time of year in 1929, most clearly illustrated by conditions on the bottom, where values, at corresponding stations along the offshore belt, increased, on the average by about $0.5\ ^{\circ}/_{\circ\circ}$ between the first of March and the third week in April (Fig. 20 A), contrasting with the decrease of $0.2\ ^{\circ}/_{\circ\circ}$–$0.9\ ^{\circ}/_{\circ\circ}$ that took place closer to land at this same time (p. 20). Meantime water of $35\ ^{\circ}/_{\circ\circ}$ had pressed in, to touch the continental edge in the sector between the offings of Delaware Bay and of Montauk, where it had not been in contact with the bottom in February (p. 17).

The data for 1931 are not as instructive as those for 1929 or 1930, from the present viewpoint, lacking observations off Chesapeake Bay for May; and off Montauk and New York for February. So far as they go, they suggest only slight intrusions of slope water in on the shelf, but enough to raise salinity on bottom by about $0.2\ ^{\circ}/_{\circ\circ}$–$0.3\ ^{\circ}/_{\circ\circ}$, along the 60–70 meter belt between the last half of February and the third week of May, on the Martha's Vineyard, and Cape May profiles; followed by a decrease between mid-May and mid-June.[17]

Lacking a general survey for February of 1932, it is not certain whether any widespread movement of the sort took place in the early spring of that year. The fact that $34\ ^{\circ}/_{\circ\circ}$ water occupied a band of about the same breadth along the outer edge of the shelf in that April, as in April of 1929, does, however, suggest something of the sort. After April, the inner boundary of $>34\ ^{\circ}/_{\circ\circ}$ water receded to the continental edge by the end of May, and oscillated back and forth, during June between the locations it had occupied in May and in April (Fig. 21).

Conditions transverse to the slope, on the Montauk (Block Island) profile for May, 1927 (Fig. 22), give a clue to what happens after a pulse of slope water slackens, for the very low bottom salinities down the slope at the time, suggests that the core of $>35\ ^{\circ}/_{\circ\circ}$ water encountered at about 100 meters at the offshore stations was such a relict, which had been cut off from its source by the expansion of a less saline water-mass, the origin of which is not clear.

*April–May mid-depths*. Vernal freshenings from the land, expanding at the surface, tend to increase the vertical gradient of salinity, both vertically and transverse to the slope. In the case of salinity, indrafts of slope water (being of opposite character, acting chiefly at the bottom and from offshore) tend in the same direction, whereas, for temperature, they tend to decrease these gradients, because their thermal effect is of the same order, from below, as that of solar radiation is from above. Neither is there any close correlation between salinity and temperature, with regard to the type of vertical dis-

[17] The observations for 1927 and 1928 throw no light on this point, lacking adequate data either for February–April, or for June.

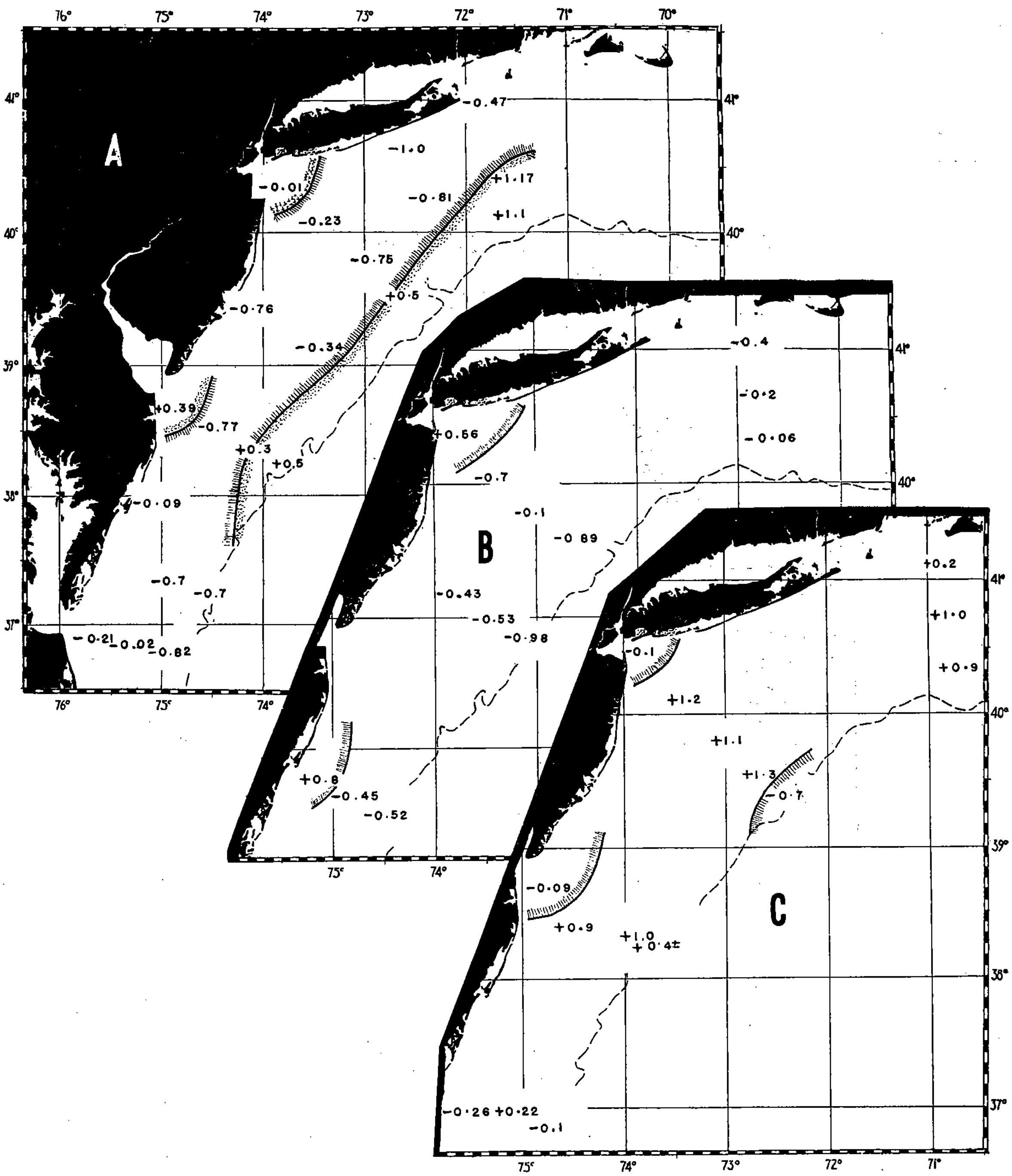


FIG. 20.—Alteration in salinity, near the bottom from winter to spring:—A, February 24–March 4 to April 14–24, 1929; B, April 23–28 to May 19–23, 1932; C, February 5–13 to April 3–11, 1930.

tribution actually existing at a given time and place, for while vernal warming of the surface is progressive throughout the spring and acts directly over the entire area, the chief incorporation of river water takes place at localities widely separated along the coast line, while indrafts of slope water vary widely from year to year, in volume, in seasonal schedule, and in the sectors of the shelf they most directly affect.

How widely the steepness of the vertical gradient existing at a given season may differ from year to year, is illustrated by the contrast between 1930 (Fig. 23), when a steep

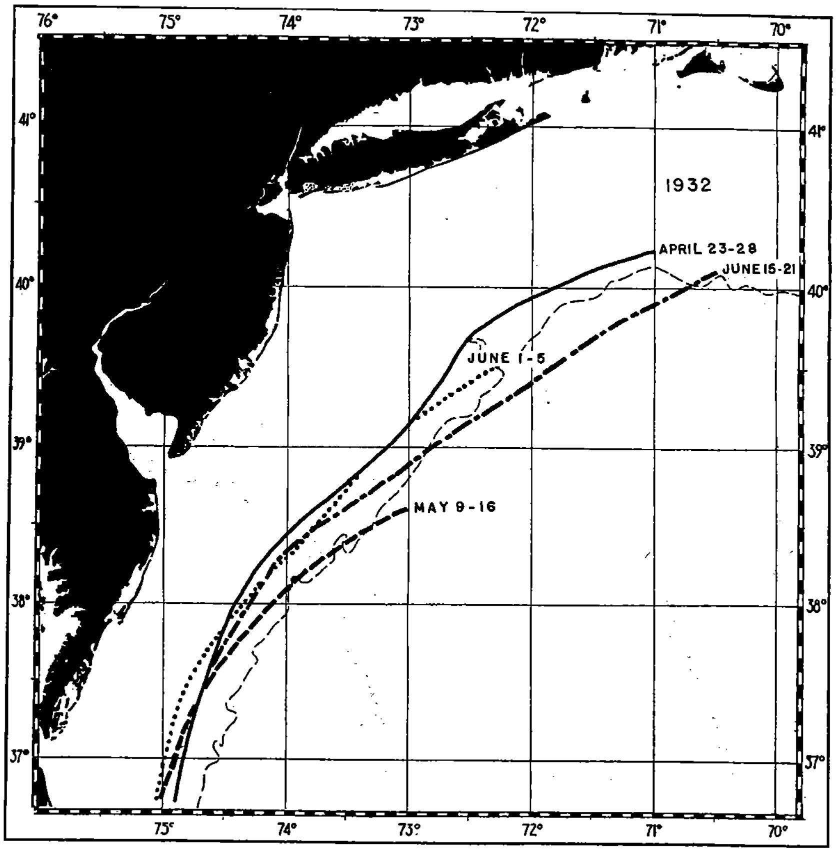


FIG. 21.—Situation of the isohaline for 34 °/₀₀, irrespective of depth, at successive dates of 1932.

gradient (confined to the vicinity of the coast of Carolina in early April) had developed off the mouths of Delaware and Chesapeake Bays and along the intervening coast-belt, by late April, soon to spread widely,[18] and 1932 when the southern sector at first experienced a change of the reverse order, though with a steep gradient developing, meantime, in the trail of the discharge from Long Island Sound.

In the inshore belt, especially off the sources of discharge from the land, the gradient may alternately steepen, slacken and steepen again, depending on the interaction between pulses of land water and the processes of vertical mixing. This was well illustrated in 1932 at Station New York I, where the difference between surface and bottom in

[18] Interrupted locally by small homogeneous (i.e., turbulently mixed) pools.

about 20 meters depth decreased from about 1.4 ‰ on April 26 to less than 0.1 ‰ on May 14, then increased again to about 2.00 ‰ on May 21, and to about 1.3 ‰ on June 2. Because of these wide, and often sudden fluctuations, coupled with the great regional irregularities shown by individual charts, it cannot be said that the state illustrated by any one of the years of record is more representative of April–May with regard to development of vertical gradient than any other, nevertheless, the following generalities seem justified.

1. Very steep vertical gradients (averaging >1.8 ‰ per 20 meters) develop only in the immediate vicinity of the sites of maximum river discharge (i.e., off New York harbor, off Delaware Bay, and off Chesapeake Bay) and close inshore along the coast of North Carolina; steepest of all (as might be expected) close to the mouth of Chesapeake Bay, where a mean gradient, surface to bottom, of >8 ‰ per 20 meters of depth has been recorded on three occasions (April 25, 1930, May 19, 1930 and April 23, 1932).

2. When very steep gradients do develop off Long Island Sound (Montauk profile), off New York, or off Delaware Bay, the areas thus characterized generally extend southward or southwestward, probably following the trails of discharge from these sources. This is illustrated by the distribution for April, 1932, May, 1930 (Fig. 23) and 1931. But the data are not sufficient to show whether this applies also to the outflow from Chesapeake Bay, because the low surface salinities responsible for steep gradients recorded to the southward along the coast of North Carolina in April, 1930 (Fig. 23), may perhaps have had their source in the discharge from a neighboring inlet (p. 27).

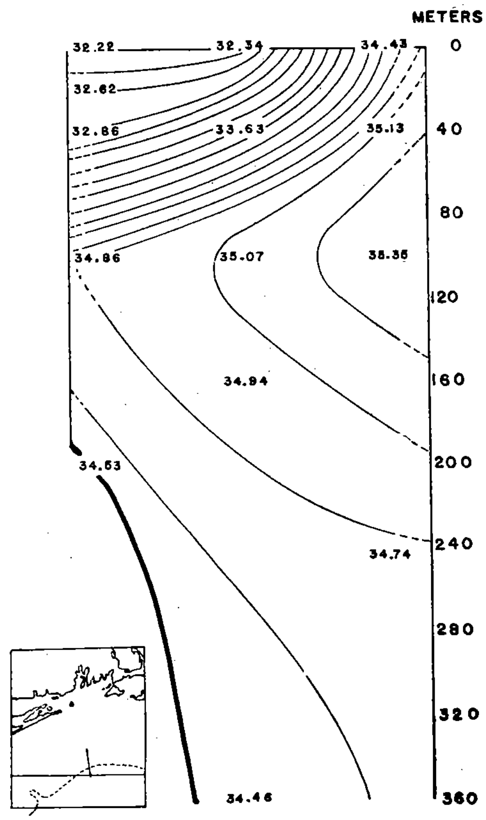


FIG. 22.—Salinity profile crossing the continental shelf, off Block Island (near Montauk Profile), May 18, 1927.

3. The vertical gradient for April and May has averaged small (usually <0.4 ‰ per 20 meters and often <0.2 ‰) over the outer half of the shelf off New York, and to the eastward, with few exceptions. On the Martha's Vineyard profile, this is the case right in to the land, a fact associated with the failure of vernal freshening appreciably to affect this sector of the shelf (p. 18). It is especially interesting that the water along the 40–80 meter belt in the offing of New York, and to the eastward, continues so nearly homogeneous through April and May because the failure of a steep gradient to develop there, like the persistence of low bottom temperatures into the summer, is associated with failure of slope water to encroach so far, on this sector of the shelf (Bigelow, 1933).

4. Along the edge of the continent, where the depth is greater (100–200 meters), the mean vertical gradient for the whole column averages small, though the total difference between surface and bottom may be considerable. But steeper gradients may develop

temporarily and locally within short sectors along this zone on occasions when water less saline than 33 ‰ extends seaward beyond the 200 meter contour, or when slope water of high salinity (>35 ‰) lies in on the edge of the shelf. Examples are the Chesapeake Bay profile, March, 1930 (mean gradient, 1.3 ‰ per 20 meters of depth); and the vicinity of latitude 39°, May, 1931 (mean gradient, 0.8 ‰ per 20 meters).

The mean vertical gradient, per unit of depth, is not an adequate expression of the degree to which a layer of discontinuity or convergence-zone is present. Obviously there can be none if the vertical gradient be nil—or—if, in shoal water, it be very small. But in deep water, the total difference between surface and bottom may be amply sufficient for the formation of a very pronounced transition-belt even though the mean rate of vertical change for the whole water column be small, if most of the gradient be condensed within a stratum of little thickness.

In the case of temperature, the progressive development of such a layer or thermocline commences in mid-spring, to culminate in late summer as described elsewhere (Bigelow, 1933). But no such general rule applies in the case of salinity, for which an increase in vertical gradient, during April and May, may be caused by freshening from above, by salting from below, or by varying combinations of the two; and for which, steepness of gradient may alternately increase, decrease and again increase during this period of the year.

The spring is, in fact, the most variable season in this respect for salinity—so variable, indeed, that average conditions cannot properly be deduced from our short series of observations. This variability appears, at a glance, from comparison of profiles, whether for different years (Fig. 24) or for successive dates for a given year (Fig. 25). In 1930, for example, the vertical gradient had become roughly uniform, by May, with the recession of >35 ‰ water near the edge of the continent off Martha's Vineyard, where the April profile showed rather a definite convergence near the 80 meter level. On the other hand a decided convergence developed during this same period off Chesapeake Bay and off Cape May, in the one case near the surface, in the other in the mid-depth, though little change took place in this respect off New York. And conditions seem, if anything, to have been still more complex in 1932, when vertical convergences, present near land off Chesapeake Bay, midway on the shelf off New York, and over the continental edge off Cape May and Martha's Vineyard in the first days of May, loosened during the following week, but when new convergences developed shortly thereafter near land off Cape May and to the northward; also midway on the shelf off Chesapeake Bay (Fig. 25).

In spite of these temporary and regional fluctuations or even reversals (e.g., as in 1932) profiles for April–May, compared with February, show an underlying tendency for individual isohalines not only to multiply in number as the vertical gradient steepens, but to run more nearly horizontal across the shelf. There is also some progressive tendency toward the development of a zone of convergence inshore, marking the boundary of the surface stratum within which the salinity has recently been reduced, in addition to the more steeply oblique convergence between shelf and slope waters offshore, which appears on many (but not all) of the February profiles as well as on many of those for the spring months. April profiles for 1930 (Fig. 19) show examples of this development early in the season; the profiles off Cape May, May 17–20, 1930, and off New York, May 16, 1931, illustrate extreme cases (Fig. 24), while in 1932 the sequence of events through May showed first development, next entire dissipation and then reëstablish-

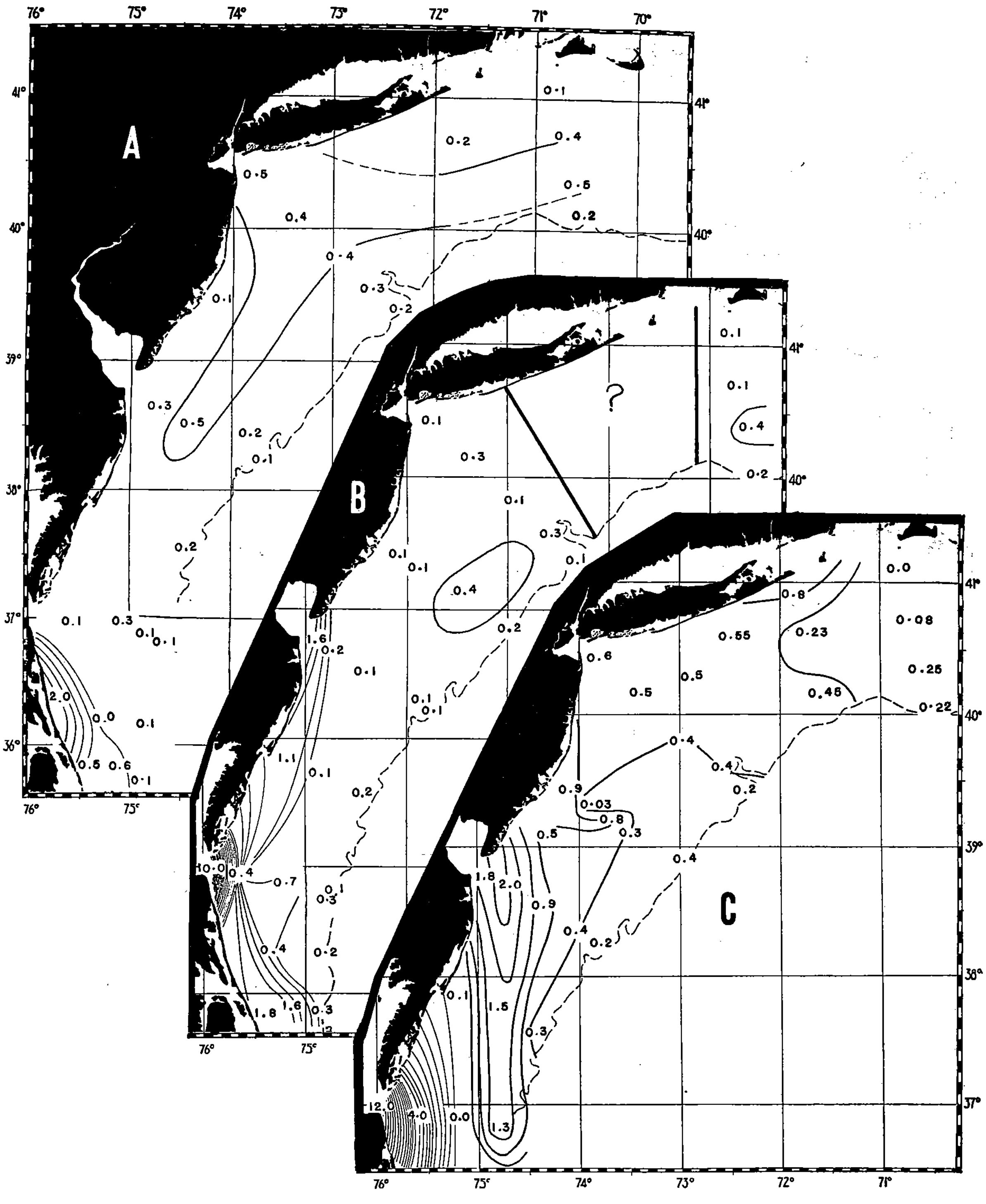


FIG. 23.—Mean vertical gradient of salinity (°/₀₀), per 20 meters of depth, between surface and bottom:—A, April 3–11, 1930; B, April 22–May 1, 1930; C, May 12–13, 1930.

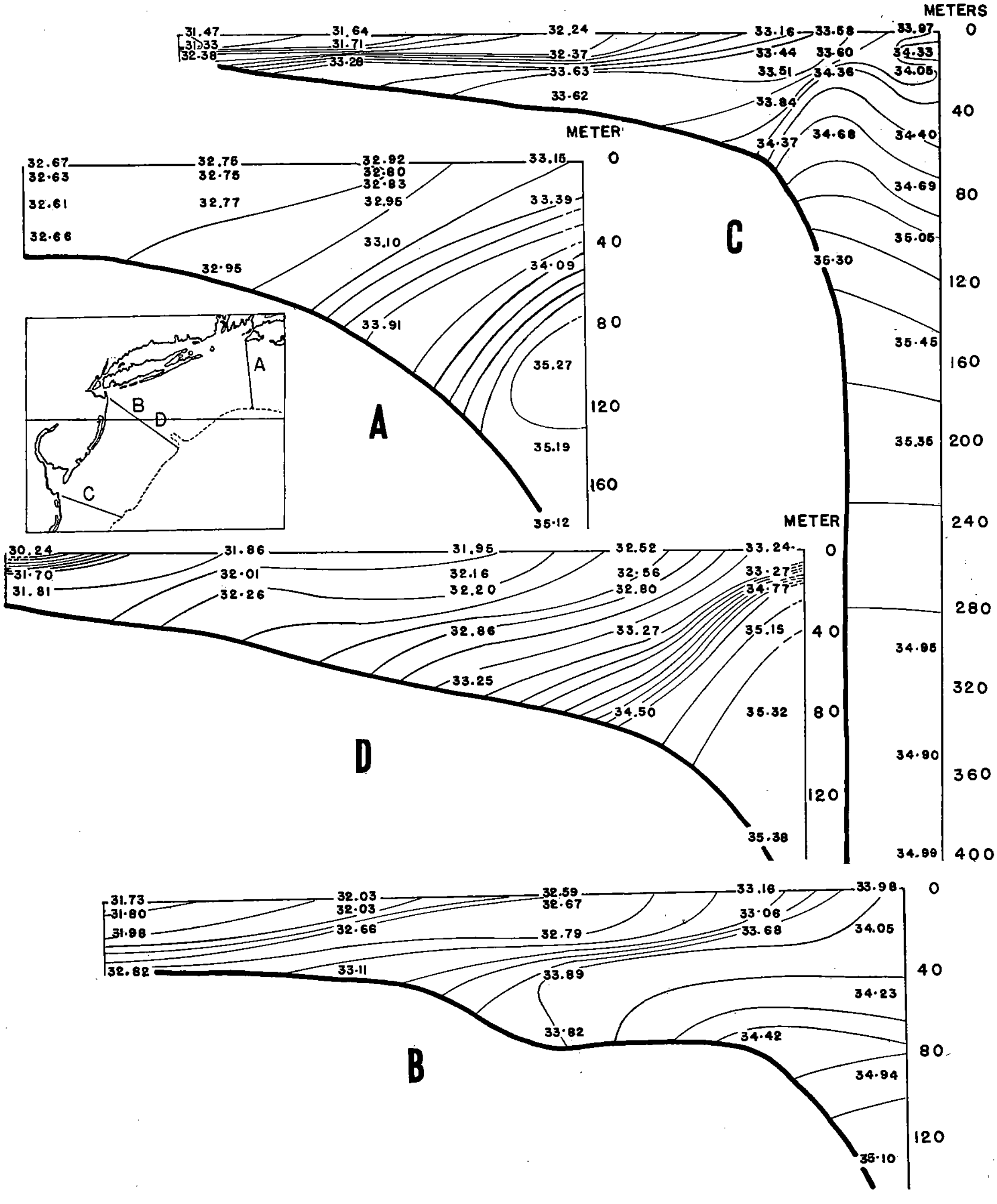


Fig. 24.—Salinity profiles crossing the continental shelf:—A, off Martha's Vineyard, May 13, 1930; B, off New York, May 16, 1930; C, off Cape May, May 17–20, 1930; D, off New York, May 17–18, 1931.

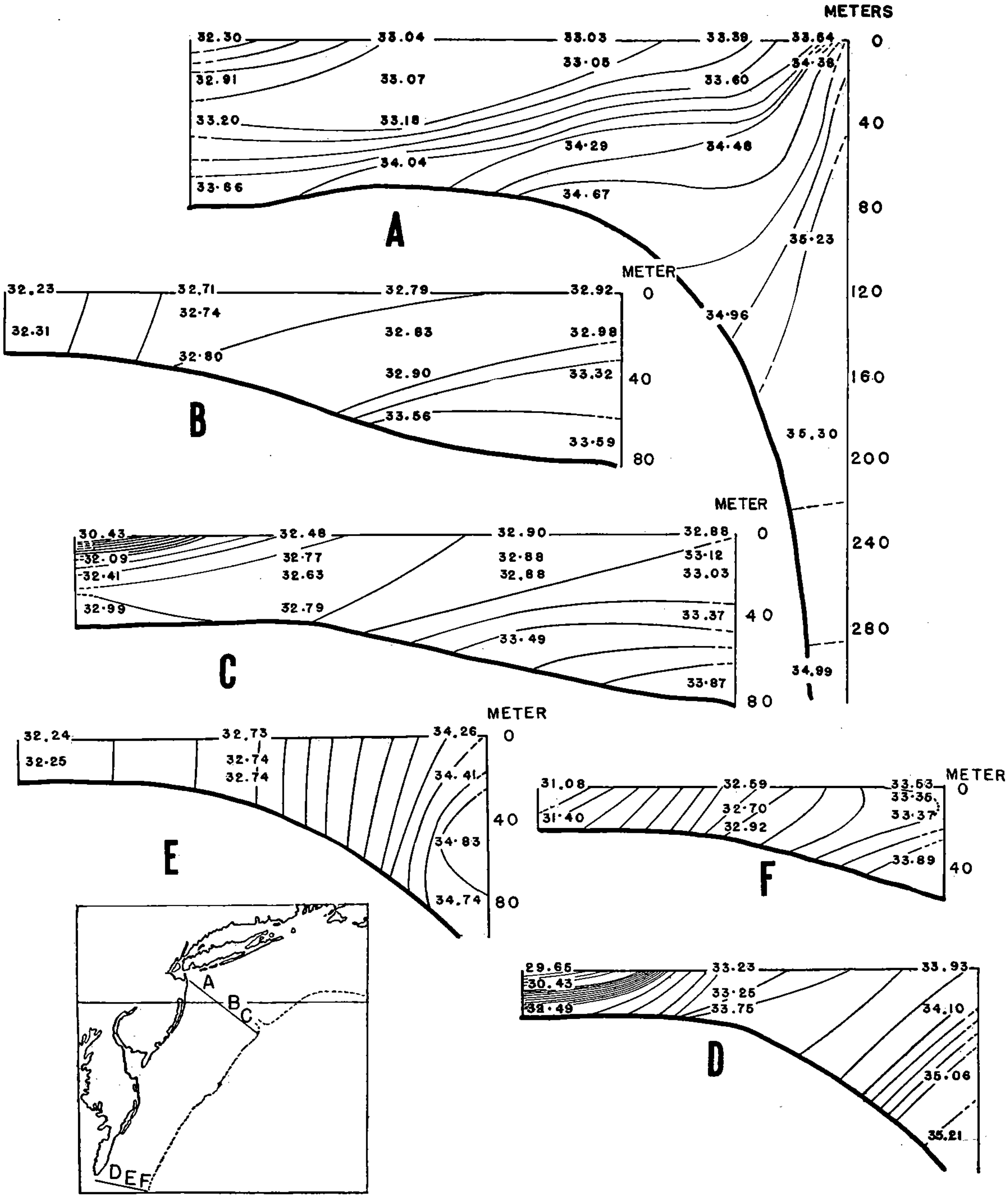


FIG. 25.—Salinity profiles crossing the continental shelf, at successive dates, May, 1932:—A, off New York, May 3–4; B, off New York, May 14–15; C, off New York, May 20–21; D, off Chesapeake Bay, May 6; E, off Chesapeake Bay, May 9; F, off Chesapeake Bay, May 23.

ment of these convergence zones (Fig. 25). The most abrupt vertical transition, so far recorded for May was of 1.50 $^\circ/_{\circ\circ}$ in 10 meters.

Only four, out of eleven profiles for April–May that have been run out across the upper part of the continental slope as far as the 1000 meter line[19] have shown interdigitation between slope and shelf waters. Since the series covers five different years, it thus appears that this type of interaction shows no great change in activity from late winter through the spring.

*May, bottom.* Maximum and minimum readings near the bottom for mid-May (Fig. 26) agree in showing uninterrupted increase from the shore seaward, partly due to increasing depth, partly also due to increasing influence of slope water, as proven by obliquity of isohalines to the profiles. The comparative uniformity of the gradient transverse to the shelf is a striking feature, whether for maximum, minimum or mean values; so, too, the crowding together of isohalines from north to south corresponding to the decrease in breadth of the shelf. But while included values are approximately the same all along (except for the immediate vicinity of the mouths of the bays and large rivers), it is characteristic also for equal values of salinity to lie not only nearer shore, but slightly higher up the sloping bottom in the southern sector than in the northern. At the 30 meter line, for example, readings have ranged from about 31.9 $^\circ/_{\circ\circ}$ to 32.9 $^\circ/_{\circ\circ}$ off New York, but from 32.8 $^\circ/_{\circ\circ}$ to 33.6 $^\circ/_{\circ\circ}$ off Chesapeake Bay. Midway out on the shelf (50–70 meter belt) the isohalines similarly swing offshore, to the eastward from the New York profile, but more nearly parallel the bottom contour to the southward.

Such data as are available for the edge of the continent (100–200 meter zone) show little gradient between the offings of Chesapeake Bay and of Martha's Vineyard, whether for maximum, for minimum or for mean values at this season.

Wide fluctuations recorded from year to year in the salinity of the bottom water close in to the mouth of Chesapeake Bay at this season, call for no special comment, being characteristic of such situations. More interesting are the considerable changes to which the bottom water is in some years subject right across the shelf from Delaware Bay, southward, on the one hand, and over the outer edge of the shelf off Martha's Vineyard on the other (Fig. 26), contrasted with its comparative constancy in the intervening sector off New York, because of the persistence of low temperatures there, and of boreal planktonic communities from spring into summer (Bigelow, 1922, 1933, Figs. 49, 51).

In the one year (1930) when general surveys were made both in February, in April, and in May (Figs. 9 A, 27) bottom salinity along the inshore belt experienced only minor fluctuations from the one month to the next, except on the Montauk profile where an increase of about 0.9 $^\circ/_{\circ\circ}$ was recorded (32.22 $^\circ/_{\circ\circ}$, Feb. 7; 33.13 $^\circ/_{\circ\circ}$, May 14) and perhaps close in to the mouth of Chesapeake Bay where the effect of land water caused low bottom salinity in that May.[20] Midway out on the shelf, however, bottom salinity considerably increased in 1930 (average change about 0.9 $^\circ/_{\circ\circ}$) from February through April (Fig. 20 C). In the most southerly sector (Chesapeake Bay profile) this increase continued through May, but that month saw a decrease in bottom salinity,

[19] Cape May and Montauk, April 14–24, 1929; Montauk (Block Island) and Cape May, May 18–21, 1927, and May 24–30, 1928; Cape May, May 17–20, 1930; Chesapeake Bay, Atlantic City and Martha's Vineyard, April 23–28, 1932; Cape May, May 4–5, 1932.

[20] No observations were taken there in that February or April.

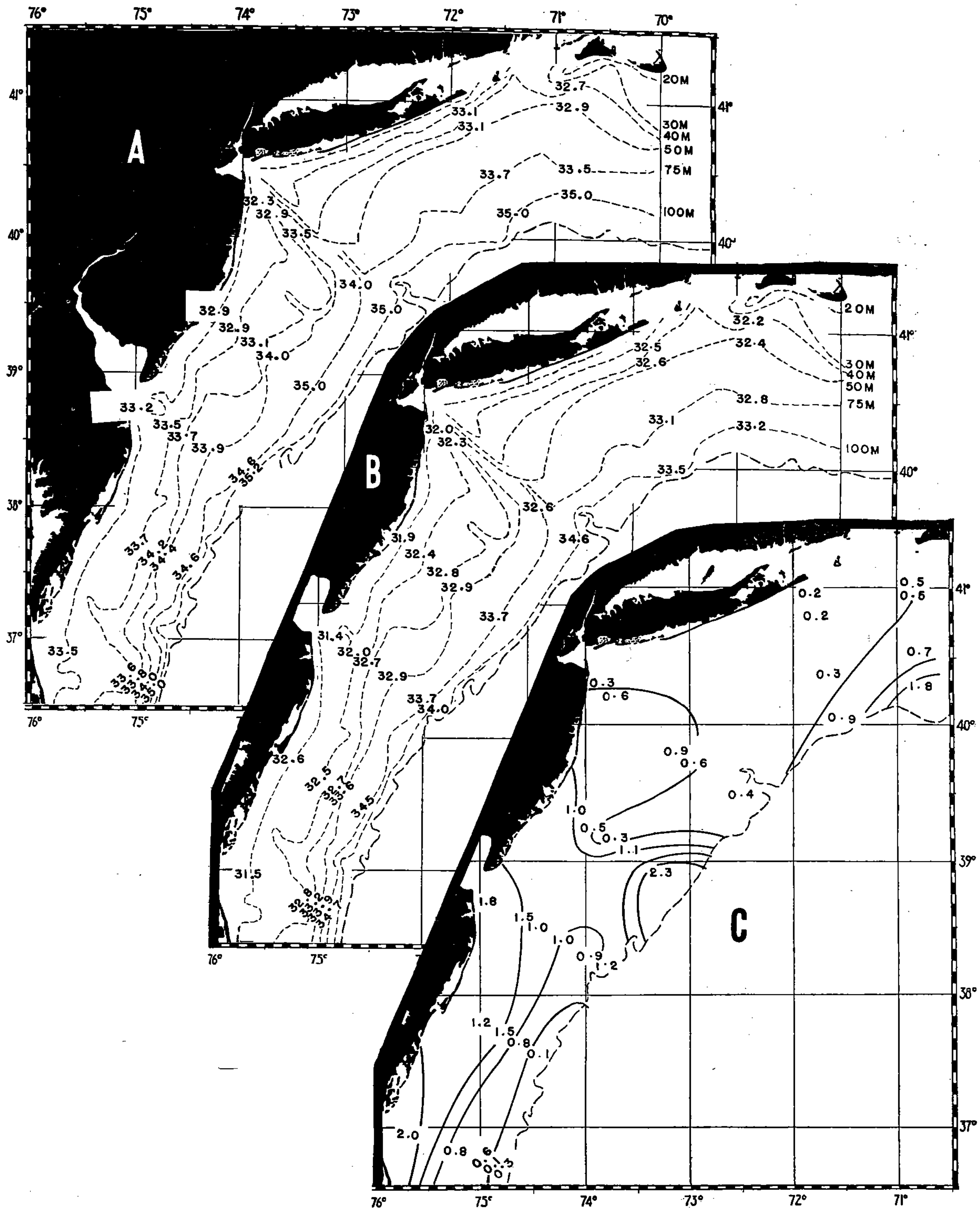


FIG. 26.—Salinity close to the bottom out to the 200 meter contour, for mid-May of 1930, 1931 and 1932, combined:—at the 30 meter, 50 meter, 75 meter and 100 meter contours (indicated by the broken lines), scaled from profiles. A, maxima; B, minima; C, difference between maxima and minima.

from the Cape May profile, northward and eastward in this zone. Still farther out, along the continental edge the vernal history for the year in question was one of small increase in some sectors (Martha's Vineyard, Cape May); of small increase followed by small

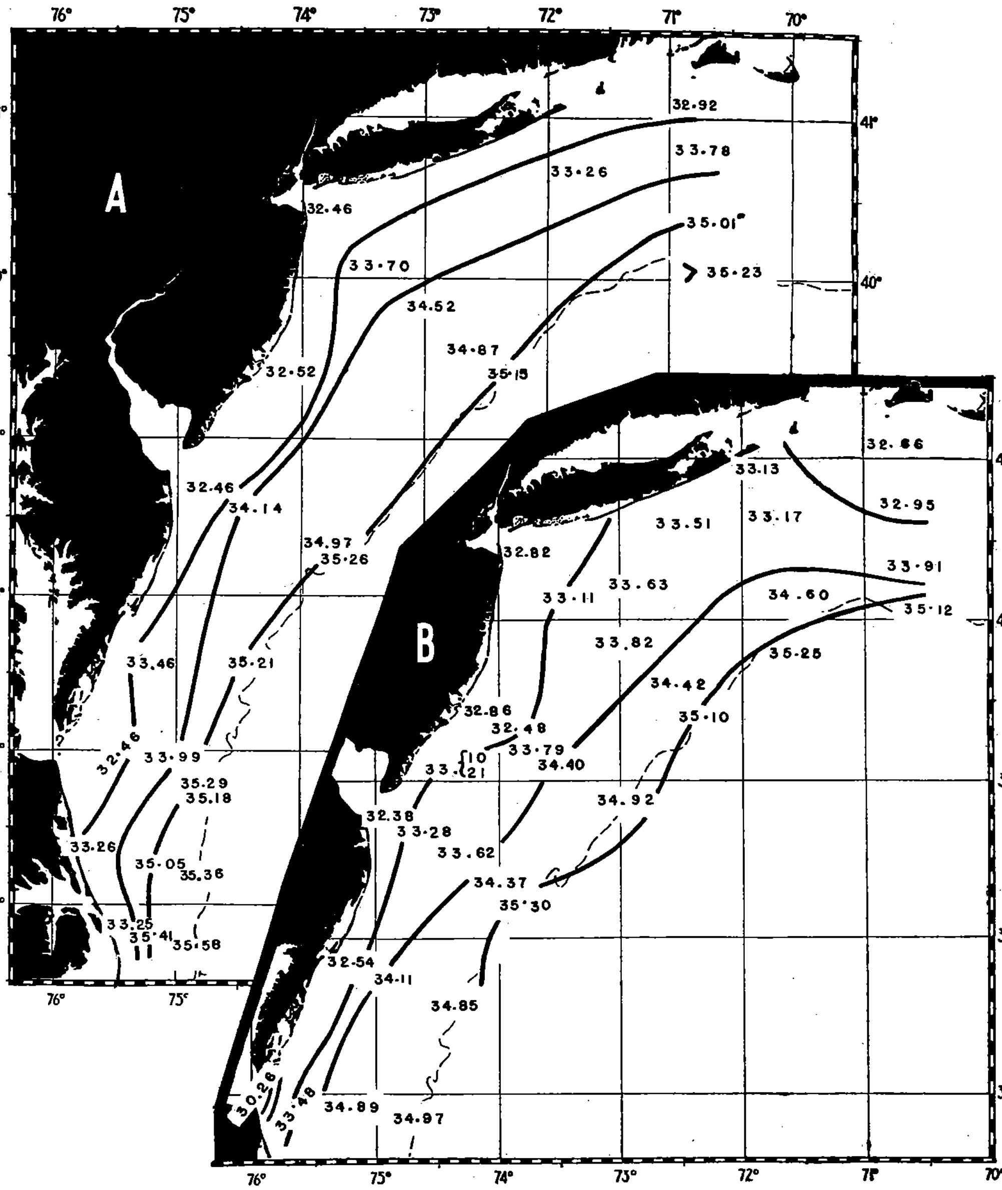


FIG. 27.—Salinity close to the bottom, out to the 200 meter contour:—A, April 3–11, 1930; B, May 12–23, 1930.

decrease in another (Chesapeake Bay); and of comparative constancy in a third (New York), depending on small shifts in the location of the inner boundary of water of 35 °/₀₀, inshore and offshore.

It seems, in short, that in a year such as 1930, when there is large indraft of slope water in April or May, this may completely offset any effect of vernal freshening from the land at the bottom, right in to the 20 meter line. And it may temporarily cause a considerable change of the reverse order (i.e., salting), along the outer zone of the shelf.

Unfortunately our seasonal picture is less satisfactory for a year of the opposite type (great river discharge, and little encroachment of slope water), as bottom data for May are lacking for 1929 and 1932. However, a considerable decrease took place in bottom salinity between February and April of the former year; a decrease extending out to the continental edge in the southern sector but confined to the inshore half of the shelf in the northern, where the coincident alteration along the outermost zone was of the reverse order (Fig. 20 A). The course of events was essentially similar in 1932 (likewise a year of weak slope water), judging from the fact that a decrease took place in bottom salinity from late April to the third week of May, over the slope as a whole, except at two inshore stations[21] (Fig. 20 B). The two profiles (Martha's Vineyard, Cape May) where the data allow seasonal comparison for 1931, also show the bottom salinity as decreasing by 0.1 °/₀₀–0.8 °/₀₀ from February to May over the inner half of the shelf, but increasing by about an equal amount near the outer edge.

Thus it appears that in years when there is but little intrusion of slope water, the salinity of the bottom water decreases by a significant amount between February and April or May over all but the outermost edge of the shelf, except at the mouths of bays or rivers where differential circulation may produce the opposite effect. This contrasts with the increase recorded in years of abundant slope water, just described (p. 40). Years of either type may experience alterations in either direction of 1 °/₀₀–2 °/₀₀, along the continental edge, depending on short-term fluctuations in the location of the boundary-zone between shelf and slope waters.

It is a fortunate chance that the observational series includes years of both types—ones also with wide variation in river discharge (Fig. 13 B, C, 16, 17), for this makes it likely that the maximum and minimum bottom values shown on Fig. 26, are extremes within which most years will fall.

## June

*Surface*. June data for the sector to the south of the Cape May profile comprise general surveys for the first of the month in 1929 and 1932; also for the mid-period in 1931, with one profile off Winterquarter, on June 16, 1932; and one near Cape Hatteras on the 21st in 1927 (tabulated on p. 92). In one of these years (1929) some expansion of water less saline than 32 °/₀₀ took place off Chesapeake Bay, during the last half of May, but had been thoroughly incorporated into the general complex during the next six weeks (Figs. 15 C, 28 A); in another (1932), the June survey showed <32 °/₀₀ water confined to the immediate offings of Delaware and Chesapeake Bays; in the third (1931) the last half of May saw a definite contraction of <32 °/₀₀. Thus it appears that salinity, in the sector between the offings of Delaware and of Chesapeake Bays, is usually at its minimum before the first of June.[22]

[21] April values for that year were close to the February expectation.

[22] The June readings for the innermost stations on the Winterquarter profile, and off Hog Island have all been higher than 32.00 °/₀₀, as follows:
Sta. Winterquarter I; May 31, 1929, 32.10 °/₀₀; June 15, 1931, 32.11 °/₀₀; June 4, 1932, 32.39 °/₀₀; June 16, 1932, 32.14 °/₀₀. Sta. Hog Island I; June 16, 1931, 32.16 °/₀₀.

On the other hand, surface values (27.00 ‰–29.00 ‰) recorded next the land just north of Cape Hatteras during the month suggest that in some years water of very low salinity spreads in that direction from Chesapeake Bay at this season, for to account for them as due to an outflow from Pamlico Sound would involve assumption that there is a northerly drift around the cape (which does not seem likely), for the discharge from the very small inlets to the north of the latter can hardly have been responsible.

Turning now to the northern part of the area, it appears from the data for 1930[23] that in a year when water <32 ‰ has already spread seaward midway out across the shelf by mid-May (Fig. 15 A), no widespread alteration is to be expected to the northward of the Cape May profile in June. At most, that particular year saw some offshore expansion abreast of Delaware Bay during the first half of June, followed by a new inrush of landwater from Long Island Sound during the last half, or later, with the isohaline for 32 ‰ otherwise swinging inshore and offshore alternately, within short sectors. But in years (exemplified by 1931 and 1932) when <32 ‰ water is confined to a narrow coastwise band in May, a great expansion of it takes place in the northern sector at some time during June. This happened between the first and third weeks of the month in 1932; between the second and fourth weeks in 1930 (Fig. 15 A). In some years (e.g., 1932) this expansion carries the isohaline for 32 ‰ right out to the edge of the continent, off New York. But the fact that, in 1930, it lay only midway out on the shelf in that sector in June, and also in July, (Fig. 15 A) shows that there is considerable variation in this respect, from year to year. It would, in particular, have been interesting to know whether salinities for May and June were notably low in 1916, as was the case for that July, but no data are available.

The fact that the area occupied by <32 ‰ water, to the northward of the Cape May profile, is at least as extensive in June as in May, and in some years much more extensive, is not accompanied by any widespread alteration, since May, in the salinity of the water next the coast, June readings at the innermost stations (including Parr's data along the coast of New Jersey) having all fallen within, or close to, the recorded limits for mid-May (Fig. 17). Very low values (27.3 ‰, 29.3 ‰) recorded near New York in 1928, contrasted with a June mean of 31.1 ‰ at Station New York I, show as great freshening from the Hudson River in June as in May, in some years. But there is no evidence that values lower than 30 ‰ were then occupying more than a small area, close in to New York harbor. And Parr's data for various dates for June, 1931, give values varying between 30.03 ‰ and 31.8 ‰ close in along the coast of New Jersey, with a mean of about 31.2 ‰.

The minima recorded for June, on the recent cruises, farther out on the shelf along the 40–50 meter line, to the north of the Cape May profile, have been 31.9 ‰ Station Montauk II, June 1 and 19, 1932; 31.2 ‰ at Station New York I on June 13, 1931; 31.6 ‰ at Station Atlantic City II, June 14, 1931.

The expansion of <32 ‰ water has not, in any June of record, reached eastward as far as the offing of Martha's Vineyard, where even the station nearest to land (Sta. I, II) has then shown only very slight evidence of surface freshening, as appears from the following summary of maximum, minimum and mean values on that profile for April, May and June of 1929–1932, combined:—

[23] No observations were made in 1929 between the 5th of June and the middle of July.

| | | | | | | No. OBS. |
|---|---|---|---|---|---|---|
| Sta. I | April | max. | 32.70 ‰ | min. 32.27 ‰ | mean 32.52 ‰ | 4 |
| | May | " | 32.67 | " 31.92 | " 32.35 | 9 |
| | June | " | 32.65 | " 32.05 | " 32.36 | 7 |
| Sta. II | April | " | 33.01 | " 32.70 | " 32.84 | 4 |
| | May | " | 32.83 | " 32.40 | " 32.61 | 10 |
| | June | " | 32.70 | " 32.23 | " 32.46 | 6 |
| Sta. III | April | " | 33.40 | " 32.81 | " 33.08 | 3 |
| | May | " | 33.61 | " 32.34 | " 32.73 | 9 |
| | June | " | 33.21 | " 32.45 | " 32.83 | 5 |
| Sta. IV | April | " | 33.07 | " 32.82 | " 32.99 | 2 |
| | May | " | 33.37 | " 32.17 | " 32.98 | 5 |
| | June | " | 33.27 | " 32.77 | " 32.99 | 4 |

And what little freshening does take place here may be temporarily reversed, as appears from the progression observed in 1932 (Fig. 10).

Still farther east, in the region of Nantucket shoals, our few June records (2 stations in 1929; 2 in 1930; 1 in 1932; and 3 late in May of 1931) show about the same general range of salinity as is usual at that same season on the Martha's Vineyard profile, grading in each case from slightly lower values inshore to slightly higher offshore. As none of these Nantucket Shoals records have been below 32.00 ‰, and as our only June survey of Massachusetts Bay also showed the surface there as uniformly higher than 32.00 ‰, right in to the land, it seems that the low salinities (<32 ‰) annually developing to the westward of Martha's Vineyard, are separated from the equally low spring values characteristic of the northeastern part of the Gulf of Maine, by a sector, extending as far as Cape Ann, within which June values seldom fall below 32 ‰.[24]

With the expansion seaward of surface water of low salinity, the inner boundary of surface water >33 ‰[25] is correspondingly shifted offshore, from the position it occupies earlier in the season until by the last half of June (Figs. 14, 28), 33 ‰ water has either disappeared from the shelf altogether, at the surface, (as happened in 1931 and no doubt also in 1927—see p. 56), or continues to encroach only here and there, over the extreme outer margin, as was the case in 1930 and 1932. Into which of these two categories 1929 fell is doubtful, lacking late June data for that year. But the fact that >33 ‰ water was continuous along the outer zone of the shelf, from about lat. 38°, nearly to the Martha's Vineyard profile at the beginning of that June, and was again found in on the shelf in the northern and southern sectors (but not in the intervening sector) in that July (Fig. 35 A), suggests that the offshore salinities may have continued somewhat higher in that year than usual.

The maximum surface values so far recorded along the continental edge in the last half of June, for the years 1929–1932, have been as follows:—Martha's Vineyard profile, 33.27 ‰; Montauk profile, 32.81 ‰; New York profile, 32.91 ‰; Atlantic City profile, 32.81 ‰; Cape May profile, 33.35 ‰. No June records have been obtained along the extreme edge of the shelf (100–200 meter belt) between the offings of Cape May and of Cape Hatteras, which leaves a serious gap. But the Hatteras profile for June 1927 (Fig. 29 B) shows oceanic water pressing much closer in toward the coast there, than on any of the profiles to the northward, with surface water of 36 ‰ overlying the 200 meter contour line.

[24] There may be local and temporary interruptions, e.g., about 30 miles west of Nantucket, May 27, 1931, surface 31.91 ‰.

[25] This may be arbitrarily set as identifying water of relatively high surface salinity, for this part of the continental shelf, as <32 ‰ may be for relatively low.

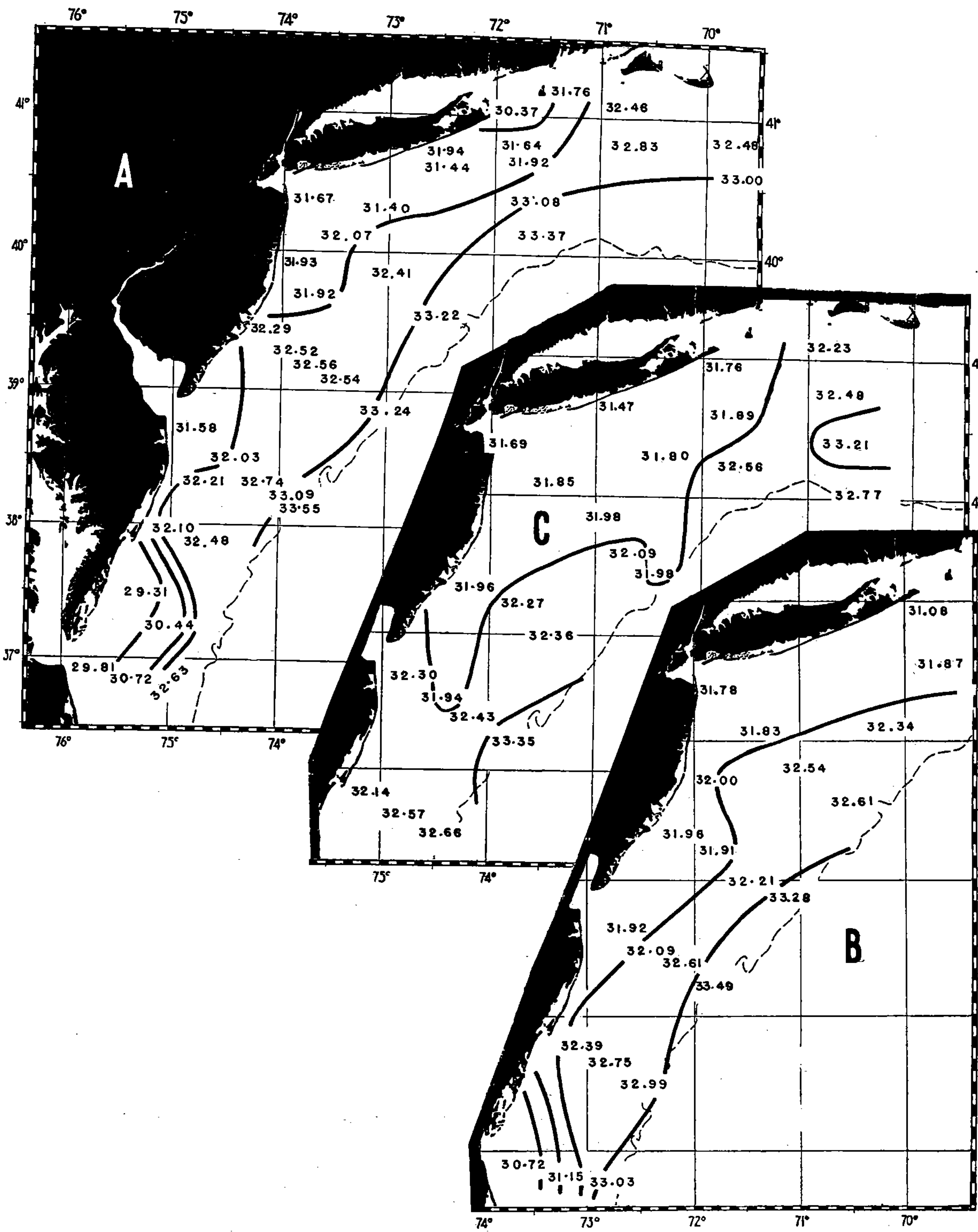


FIG. 28.—Salinity at the surface:—A, May 28–June 5, 1929; B, June 1–5, 1932; C, June 15–21, 1932.

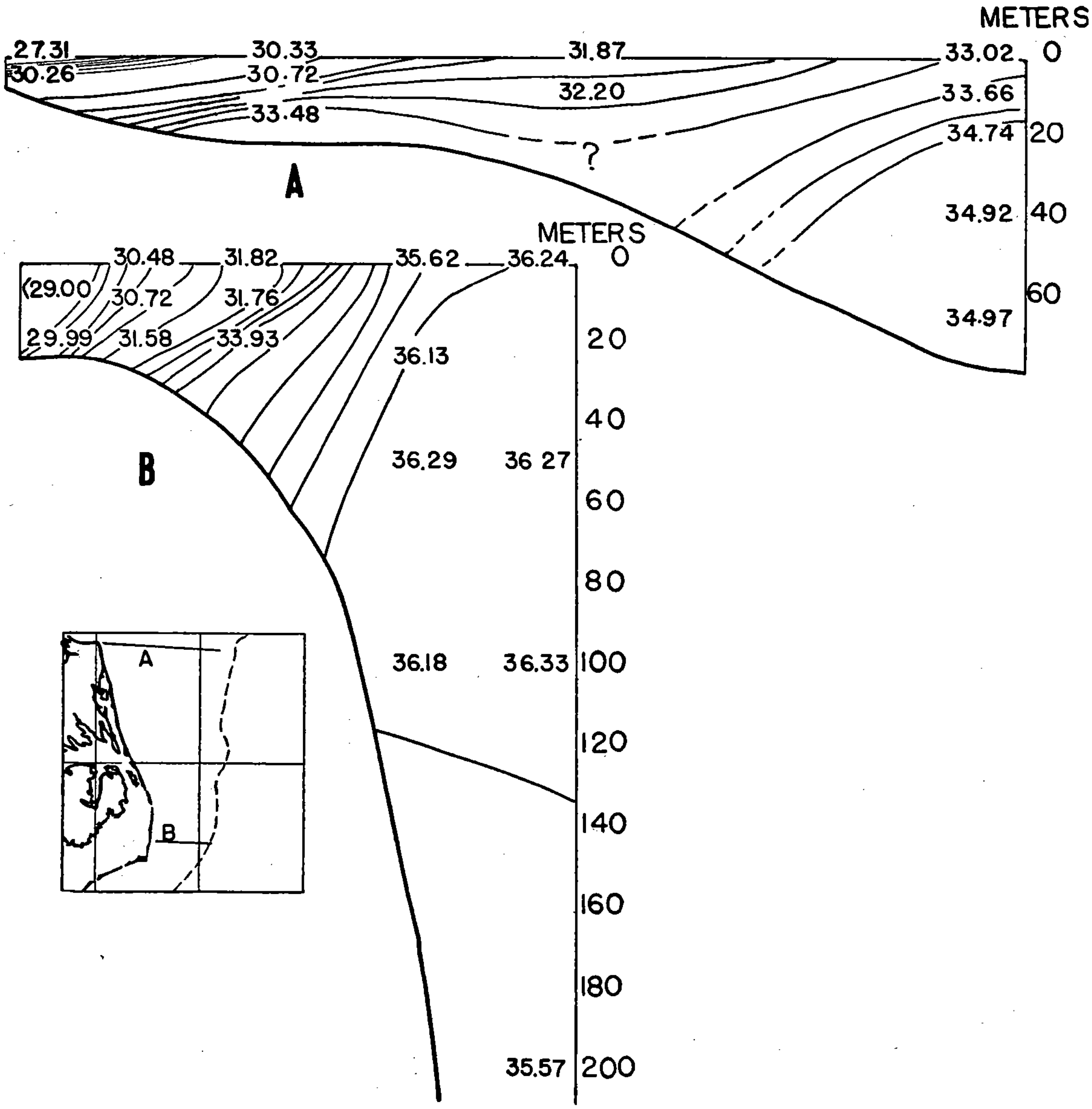


Fig. 29.—Salinity profiles crossing the continental shelf:—A, off Chesapeake Bay, May 18–19, 1930; B, off Cape Hatteras, June 21, 1927. *Because of crowding, isohalines are given for every 0.5 °/₀₀ only.*

*Mid-depths.* Profiles for early, mid-, and late June (Figs. 30, 31) show a general tendency toward a smoothing out of the wide contrasts that are characteristic of May, with only one June station showing a mean vertical gradient, surface-bottom, of more than 1.00 °/₀₀ per 20 meters.[26] On the other hand, June charts show no extensive areas with negligible gradients (<1.00 °/₀₀ per 20 meters), such as occupied the whole breadth of the shelf, between latitudes 39° and 41° in mid-May of 1930 (Fig. 23 C):—where, in fact, the mean gradient increased in that year to 0.3 °/₀₀–0.8 °/₀₀ per 20 meters by the

[26] No data available for June for the inshore station off Chesapeake Bay.

third week of June (Fig. 31). Nevertheless, year to year differences in regional distribution still continue wide in this respect, as illustrated, on the one hand, by the year 1931, when it was the mid-belt of the shelf, between the offings of New York and of Delaware Bay, that showed the steepest mean gradients, and on the other by 1932, when the maxima were localized in distinct pools, close inshore; 1931 showed an intermediate state.

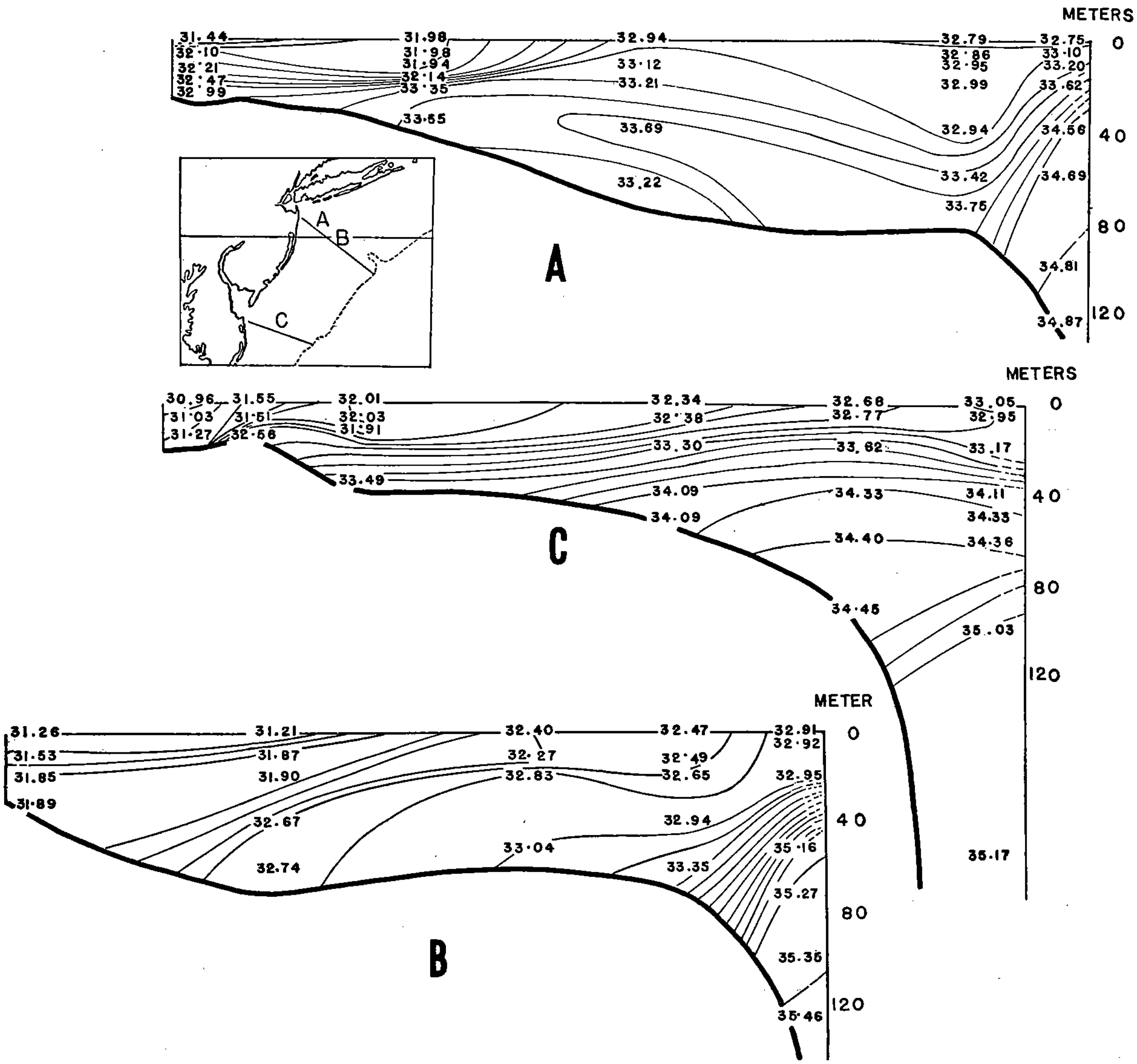

FIG. 30.—Salinity profiles crossing the continental shelf:—A, off New York, June 8–9, 1930; B, off New York, June 13, 1931; C, off Cape May, June 11, 1930.

On the whole the contrast is more definite in June, than in May (Fig. 23), between the comparatively homogeneous water that occupies the whole breadth of the shelf to the eastward of longitude about 72°, spreading thence southward as a narrowing tongue along the outer edge of the shelf, and the belt of steeper gradient that intervenes between the latter and the coast.

By the middle of June, surface warming results in the development of a well-defined thermocline throughout the whole area (Bigelow, 1933, Fig. 31) separating the upper stratum, which is close to homogeneous, from a bottom stratum in which the vertical gradient of temperature also averages small. But the underlying pattern of salinity for June frequently includes the same two zones of convergence, between coast and shelf water, and between the latter and slope water, that may, or may not, be present in May

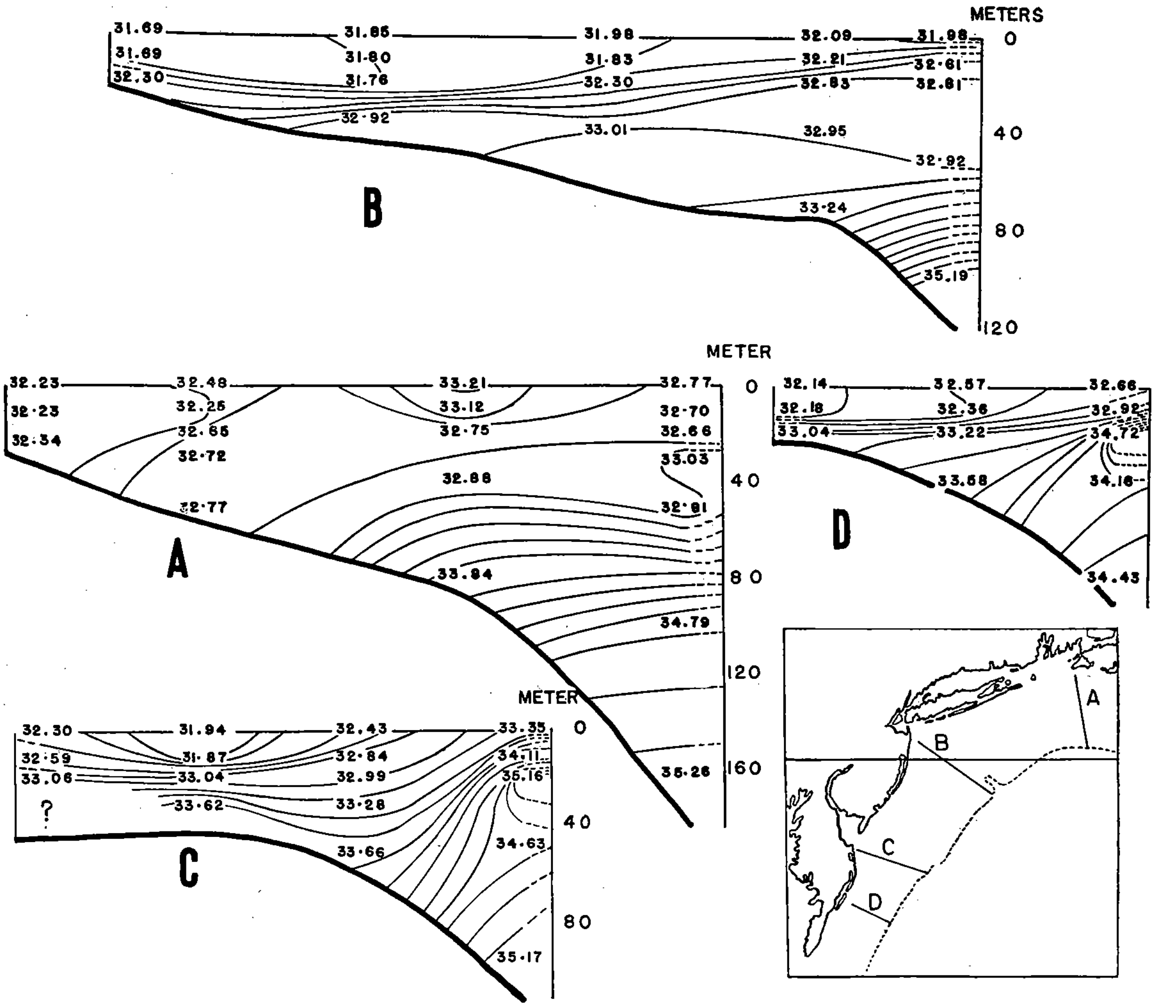


FIG. 31.—Salinity profiles crossing thecon tinental shelf, June 15–21, 1932:—A, Martha's Vineyard; B, off New York; C, off Cape May; D, off Winterquarter.

(even in April) as already described (p. 36). By the middle of June, the offshore member of this pair has appeared often enough on such of the Montauk, New York and Cape May profiles as reached out to water of 34 °/₀₀, to be accepted as characteristic of that sector at the time. Probably this applies equally as far southward as Cape Hatteras, (unless temporarily masked by local irregularities or short term pulsations), for the convergence in question appears also on profiles off the cape for June 21, 1927 (Fig. 29), and off Winterquarter for June 4–5, 1932 and June 15–21, 1932 (Fig. 31 D).[27]

[27] These are the only June profiles to the south of Cape May that have been extended seaward as far as water of 34 °/₀₀.

The inshore convergence may be abrupt, in fact so much so as to deserve the name of a true discontinuity surface—witness a vertical alteration of 1.2 °/₀₀ in a vertical distance of only 5 meters (Fig. 30 A). At the other extreme, it may be so weak as hardly to be recognizable (Fig. 30 B). In any case, it seems never to extend eastward much past the Montauk profile, for it does not appear on any of the mid-June profiles off Martha's Vineyard (Fig. 31 A); nor would it be expected to do so, judging from the fact that land-discharge is but little in evidence there. The offshore convergence may, however, be as strongly developed there as anywhere.

June profiles have shown wide variation in the degree of obliquity of individual isohalines as well as in the general trend of the latter, depending chiefly on the extent to which coast water has recently spread offshore, contrasted with counter movements of slope water beneath. At the one extreme, illustrated by the New York profile for June 17–18, 1932, and the Cape May profile for the 11th of the month, for 1930 (Fig. 30 C, 31 B), the isohalines as a whole may run close to horizontal right across the shelf. It is more usual, however, for them to rise more steeply surfaceward and seaward, both at the inshore and at the offshore ends of individual profiles; sometimes very steeply indeed. And it is probable this would invariably be found to be the case on any profile extending offshore far enough to reach out beyond any recent dilution by coast water.

Attention should also be called to the interdigitations between lower values and higher values illustrated at the offshore ends of several of the June profiles (Figs. 31 A, C, D), as also on those for May (p. 40, Figs. 22, 24 A, C). As summer draws on, such interdigitations in the case of temperature, take the prevailing form of a shelf-like intrusion of relatively cold water, indenting seaward into warmer (see, for example, Bigelow, 1933, Figs. 27 A; 28 A, B; 31 A; 42 A, C; 43 B). The situation with regard to salinity is much less regular in this respect. In 1932, for example, the vertical succession, from the surface downward, at the outer station off Martha's Vineyard on June 20, was from a higher value (32.77 °/₀₀) at the surface to lower (32.66 °/₀₀) at 20 meters, then to higher again (33.03 °/₀₀ at 32 meters), to lower (32.81 °/₀₀) at 50 meters, below which a considerable increase was recorded (Fig. 31 A). And a complex situation was likewise encountered on the Cape May profile, on that same cruise (Fig. 31 C). On the other hand the same profile, for June 11, 1930, showed an uninterrupted increase in salinity, with increasing depth (Fig. 30 C).

The seasonal relationship between temperature and salinity in this respect is illustrated in its simplest form by the Martha's Vineyard profile, for 1931 (Fig. 32) on which the isolines for 9° and for 34 °/₀₀ (arbitrarily taken as marking the inshore boundary of slope water there in winter) closely coincided from February through April (showing meantime a decided inshore encroachment) but thereafter strongly diverged, as the 9° line was shifted in the one direction by solar warming, whereas the 34 °/₀₀ line was shifted in the opposite direction (offshore) by the freshening effect of land drainage. This type may be described as basic for the whole sector, south to the Cape May profile.

Obviously, if mass movements of water take place, the picture will be altered. On the Cape May profile for example,[28] the initial separation between the isolines caused by solar warming was followed by an encroachment of water colder than 8° between late May and mid-June, offshore, and down the slope into the area occupied by salinity >34.2 °/₀₀. The most probable explanation is a drift from the northeast, where the slope water had been chilled below 9° shortly previous, as shown by the Martha's Vineyard profile.

[28] In this case 9° corresponds most nearly to 34.2 °/₀₀.

Still more strikingly is the picture altered in the eastern part of the area, in years when floodings from the east are in large volume, as is illustrated by the seasonal succession on the Martha's Vineyard profile for 1930 (Fig. 33). The fact that both the isolines were depressed in this case, between February (when they were closely coincident) and early April, shows the efficiency of flooding from the east in freshening as well as in cooling the upper strata. Still further depression of the 9° isotherm over the continental edge, during April, but with no corresponding alteration of salinity there, points to another similar drift, at greater depth, from the east where water of 34 °/₀₀ no doubt had been colder during the preceding winter than at the locality in question. This drift would not have been revealed either by temperature or by salinity, taken alone.

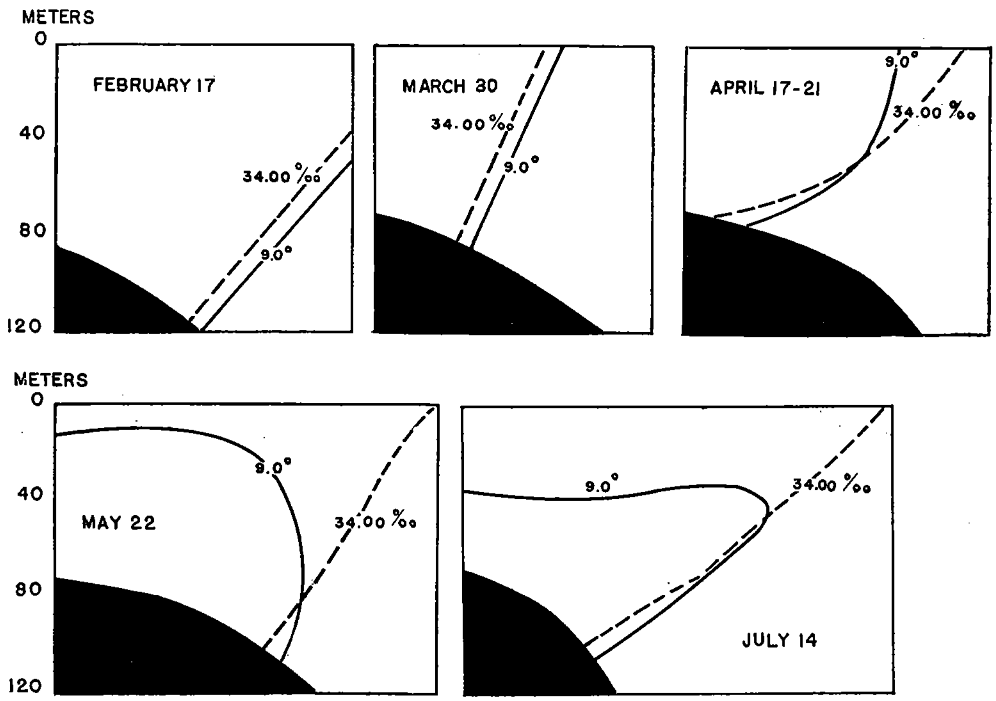


FIG. 32.—Profiles crossing the outer part of the continental shelf, off Martha's Vineyard, to show the mutual locations of the isolines for 9° and 34 °/₀₀, at successive dates in 1931.

The fact that the isolines thereafter assumed the relative positions characteristic of the late spring of years when mutual shifts of water-masses are minimal, points to early May as having been a period of relative quiescence, in 1930 also. But the subsequent development, shoreward, of a shelf-like intrusion, from May to June, at the 60–70 meter level, without corresponding rise of temperature, points to renewal of the drift, along the slope from the east, at this level. And this, it seems, continued into July, judging from the fact that the two isolines continued to spread apart in the bottom stratum.

Along the edge of the continent to the southward of Delaware Bay, the interplay of temperature and salinity as seen in profile is of still another type. Here the water is so shoal across most of the shelf and the whole column warms so rapidly right down to bottom, that the temperatures (about 6°–7°) that correspond to 34 °/₀₀ there in winter have entirely vanished by the last of April, or by May at latest (Bigelow, 1933, Fig. 10 B, C).

*Bottom.* Different years (1930, 1931, 1932) have shown wide differences in the succession of bottom salinity from May through June, primarily dependent on variations

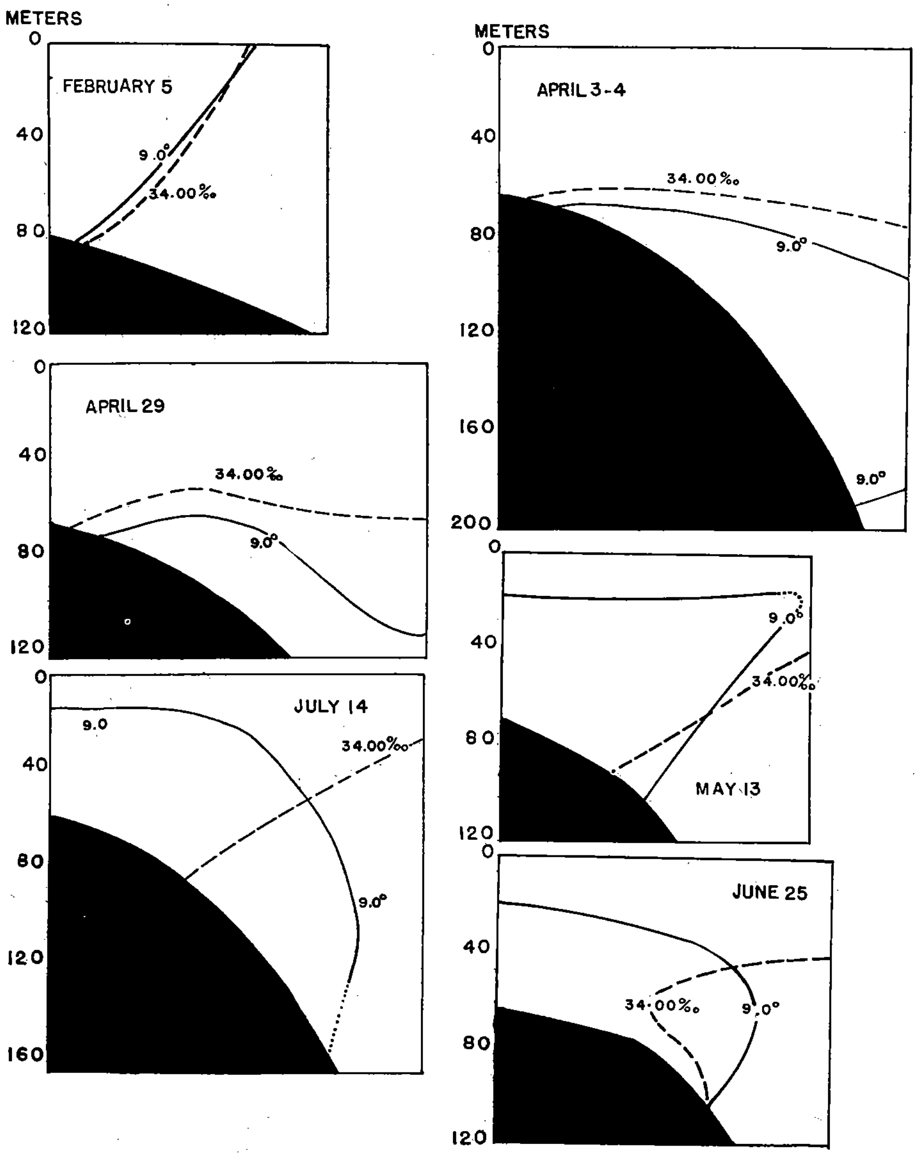


FIG. 33.—Profiles, crossing the outer part of the continental shelf off Martha's Vineyard, to show the mutual relations of the isolines for 9° and 34 °/₀₀ at successive dates in 1930.

in the expansions and contractions of slope water along the outer part of the shelf (p. 43), and on the degree to which their effects extend inshore.

In 1932, the salinity of the bottom water increased by 0.2 °/₀₀–0.5 °/₀₀, over the shelf generally, out to the 75 meter contour, between the offings of Atlantic City and of

Winterquarter (likewise off Martha's Vineyard), but either decreased by about as much, or suffered little change in the intervening sector (New York and Montauk profiles). In 1931, there was decided decrease (by 1.5 °/₀₀–2.00 °/₀₀) along the outer edge of the shelf in the offings of Martha's Vineyard, Montauk, and Atlantic City; counterbalanced,

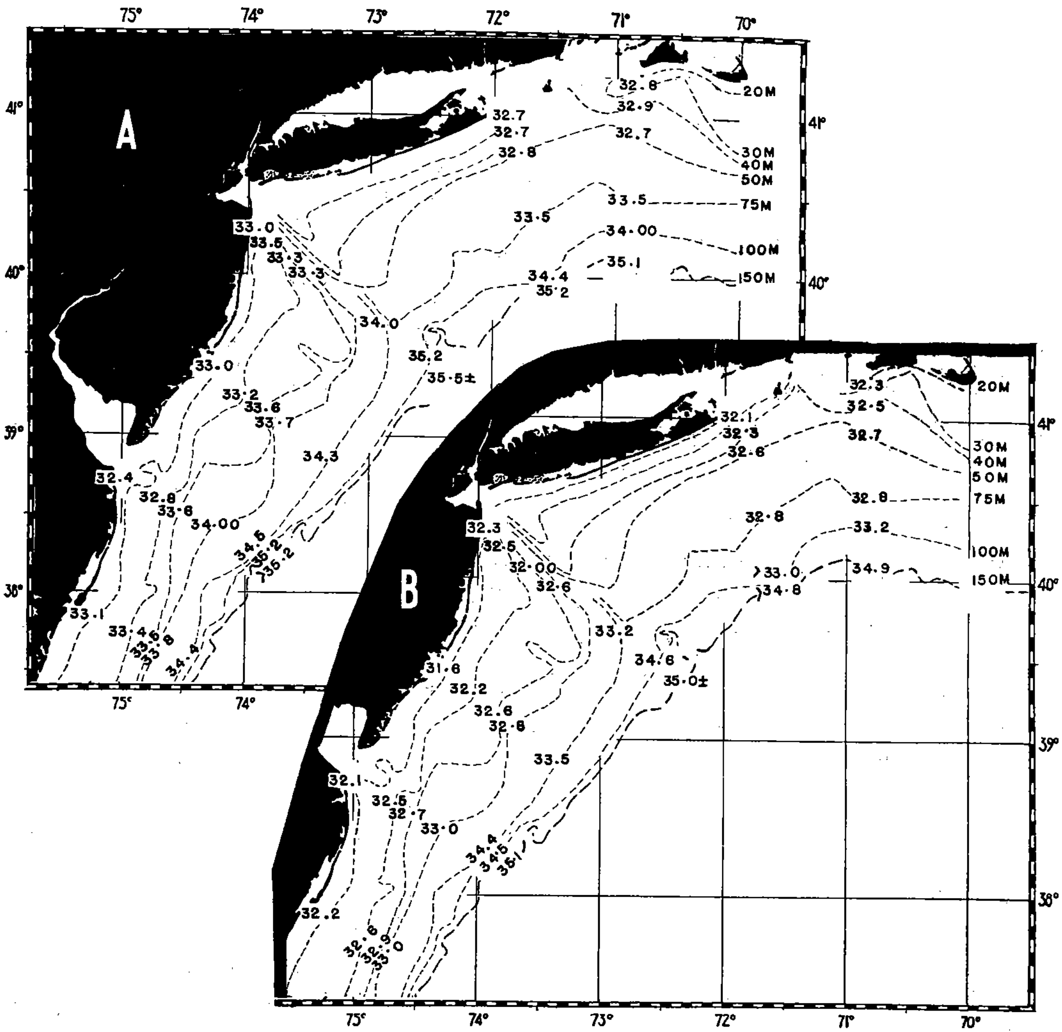


FIG. 34.—Salinity close to the bottom (out to the 200 meter contour) at the 20 meter, 30 meter, 40 meter, 50 meter, 75 meter, 100 meter and 150 meter contours (indicated by the broken lines), for mid-June, of years 1930, 1931 and 1932, combined, scaled from profiles:—A, maxima; B, minima.

however, by an increase (0.2 °/₀₀–0.7 °/₀₀) at the same relative position off New York, alterations elsewhere being small. And in 1930, a decrease was registered over the outer half of the shelf as a whole, southward as far as the Cape May profile;[29] though with little change along the continental edge, contrasted with slight increase next the land

[29] No June data farther south for that year.

off New Jersey and New York. In spite of these fluctuations, the three years, in combination, suggest an increase as characteristic off the coast of Virginia, contrasted with decreases off Delaware Bay and on the Montauk profile where the effects of land water from Delaware Bay and from Long Island Sound still continue. Bottom salinities also decrease on the outer part of the shelf in years (e.g., 1930) and within sectors where slope water more saline than 34 ‰ has encroached during the preceding month, and then either receded, or been incorporated. And it is under these last conditions that the greatest decreases (1.00 ‰–2.00 ‰) have been recorded from May to June, in bottom salinity. Elsewhere on the shelf the bottom water may either be slightly more, or slightly less saline in mid-June than in May.

Judging from available data, bottom salinities for mid-June, may be expected to fall between the values shown in Figure 34, in most years. In spite of the wide yearly range of variation, these show a definite regional consistency, with lowest values (invariably <33 ‰, and often <32.5 ‰) concentrated off the mouth of Delaware Bay, and inshore in the eastern sector of the area, while the bottom midway out on the shelf has invariably been >32.5 ‰ and often >33 ‰, rising to >34.5 ‰–35.00 ‰ along the continental edge. Such of the June profiles as extend out far enough to touch water of 35 ‰ show that the isohaline for that value, to the northward of latitude 37° may touch bottom as far in as the 80 meter contour; or as deep down as 130 meters, i.e., much as in May. None of the June profiles, however, have been run seaward far enough to show how low down the slope the lower boundary of 35 ‰ bottom water lies at this time of year.

The late-June profile, off Cape Hatteras, for 1927 (Fig. 29), is especially interesting in this connection for while it shows a very low bottom salinity inshore (<30 ‰ at 20 meters), offshore values, at corresponding depths are much higher there (>36 ‰ at 50–150 meters), than anywhere to the northward, at this season or at any other. And while this is our only summer profile for this general region, it is enough to show that the triangular mass of slope water is entirely pinched off, at all depths, in the offing of the cape, in summer as in winter (p. 8), leaving the transition abrupt, from coastal to typically oceanic water.

## July-August

General surveys of the region, for July-August, were made in 1913, 1916, 1927 and 1929; those for 1928, 1930, 1931 and 1932 being restricted to the northeastern part, as are most of the numerous steamship records (p. 3).

*Surface.* The fact that the offshore boundaries of surface water <32 ‰ occupied approximately the same locations to the northward of latitude 39°,[30] in mid-July (Fig. 35 C) as in mid-June (Fig. 15) of the years 1930, 1931 and 1932; and also from year to year, with >33 ‰ water either entirely outside the shelf (e.g., 1932) or overlying only the extreme edge of the latter (1931) shows that conditions continued decidedly stable from the one month to the next during these years. This may also have been the case in 1913 and 1916, years for which no data are available for June. This accords with the facts that the trend, in mean values, along the line New York-Nantucket Lightship, is roughly stationary from June to July (Fig. 11), and that the minimum near New York is about the same for July (27.5 ‰) as for June and for May (p. 22). Individual years may, however, show considerable variation in this respect. Thus in 1929, the area less saline than 32 ‰ not only contracted considerably in extent between early June and

[30] These July surveys did not extend farther south than this.

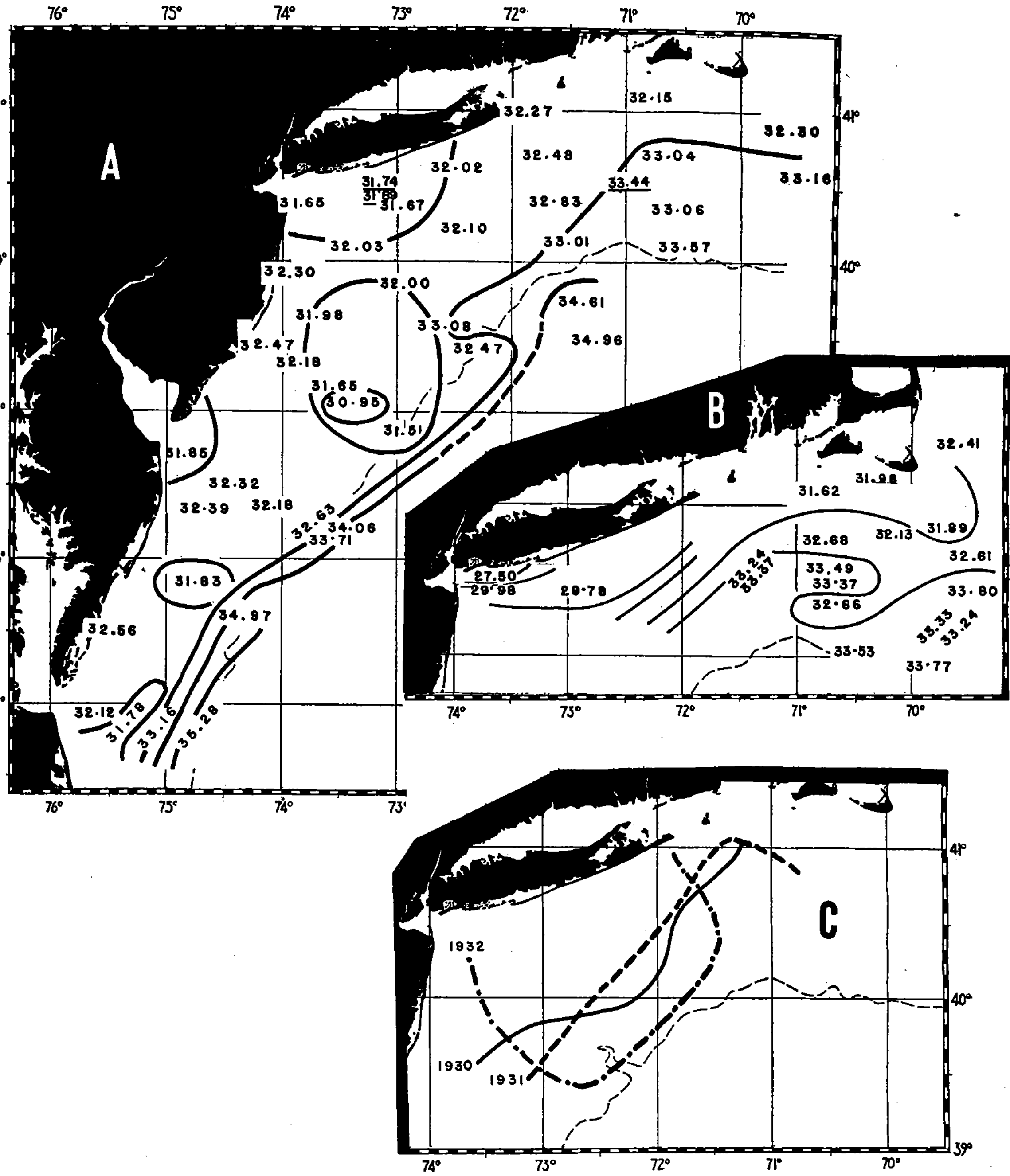


FIG. 35.—Salinity at the surface in July:—A, July 13–25, 1929; B, July 8–28, 1928; C, location of the isohaline for 32 °/₀₀ in mid-July of the years 1930, 1931 and 1932.

mid-July, but broke into three separate pools, one of them lying well out on the shelf, instead of basing on the land as is the invariable rule earlier in the season (cf. Fig. 35 A with Fig. 15). And in 1928, the isohaline for 33 °/₀₀ shifted some miles inshore, in the sector between New York and Nantucket Lightship, though with little change in surface values next the land. This season may thus see wide alteration of the salinity-pattern in some years, though not in others.

The situation in 1913 suggests that whatever change does take place at this season normally tends toward equalization of surface values, combined with a small increase in salinities in the coastal belt as the increment of land water decreases. And we have some measure of the effect of the latter event off the mouth of Delaware Bay and vicinity, during the summer of 1929, in Parr's data, which show the following increase in salinity.

| Locality | Early July | Late July |
|---|---|---|
| McCries Shoal | 31.15 °/₀₀ | 32.34 °/₀₀ |
| Close to Cape May Point | 29.88 | 32.05 |
| Five Fathom Bank | 32.09 | 32.21–32.88 |
| Off Wildwood, N.J., 3–4 fathom line | 32.32 | 32.56 |

On the other hand the extremely low surface values recorded in 1916[31] and 1927 (Figs. 36, 37) suggest that, in exceptional years, the freshening effects of discharges from the land may not reach their maximum until well on into the summer.

Inshore, in years of relatively low, or of normal salinity, the lowest values, at this season, have been recorded off the mouth of Chesapeake Bay,[32] where continued drainage was responsible for a surface reading of slightly less than 24 °/₀₀, seven miles out from the land on August 21, 1916; 29.25 °/₀₀, also on July 29, 1913. Values about as low (27.50 °/₀₀–29.98 °/₀₀ in July, 1928; 28.68 °/₀₀, July 12, 1930) have also been recorded off New York harbor, showing the effect of the discharge from the Hudson River. In other years (1929 for example), the outflow from the bays may have passed its peak so long previous, that by July the surface is about as saline off Chesapeake Bay and off New York, as off Delaware Bay, and only slightly less so than along the intervening sectors of coast line. Away from the immediate vicinity of the sites of discharge, the longshore salinity ranges at this season between slightly below 31 °/₀₀ and slightly above 32.5 °/₀₀ in different years, with no definite north and south gradient.

Judging from the years that show extreme conditions, in the one direction (1928, 1929, Fig. 35), or in the other (1916, 1927, Fig. 37); the surface, along the midzone of the shelf, is not likely to be less saline than 30.5 °/₀₀–31.5 °/₀₀, or more saline than 32.5 °/₀₀–32.8 °/₀₀, in July and August, except in the offing of Martha's Vineyard, where values above 33 °/₀₀ may press well in, during summers of high salinity (e.g., 1914; Bigelow, 1917, Sta. 10358–10361; 1928, Fig. 35 B).

In summer the region of Nantucket Shoals is set apart so sharply from the region to the westward, by low surface temperature (Bigelow, 1933, p. 56), that it is worth emphasizing that there is no such contrast for salinity—all July and August readings for the surface, for the general region of the shoals, out to the 100 meter line, have fallen between about 31.6 °/₀₀ and about 33 °/₀₀; the lower values inshore, the higher offshore. This agrees very closely with the situation as existing on the Martha's Vineyard profile, across the smoother bottom to the westward, in the same years.

[31] No data for that year prior to late July.

[32] Cowles (1930) records surface salinities of 24.9 °/₀₀–26.9 °/₀₀ in the mouth of Chesapeake Bay close to Cape Charles in July 1916.

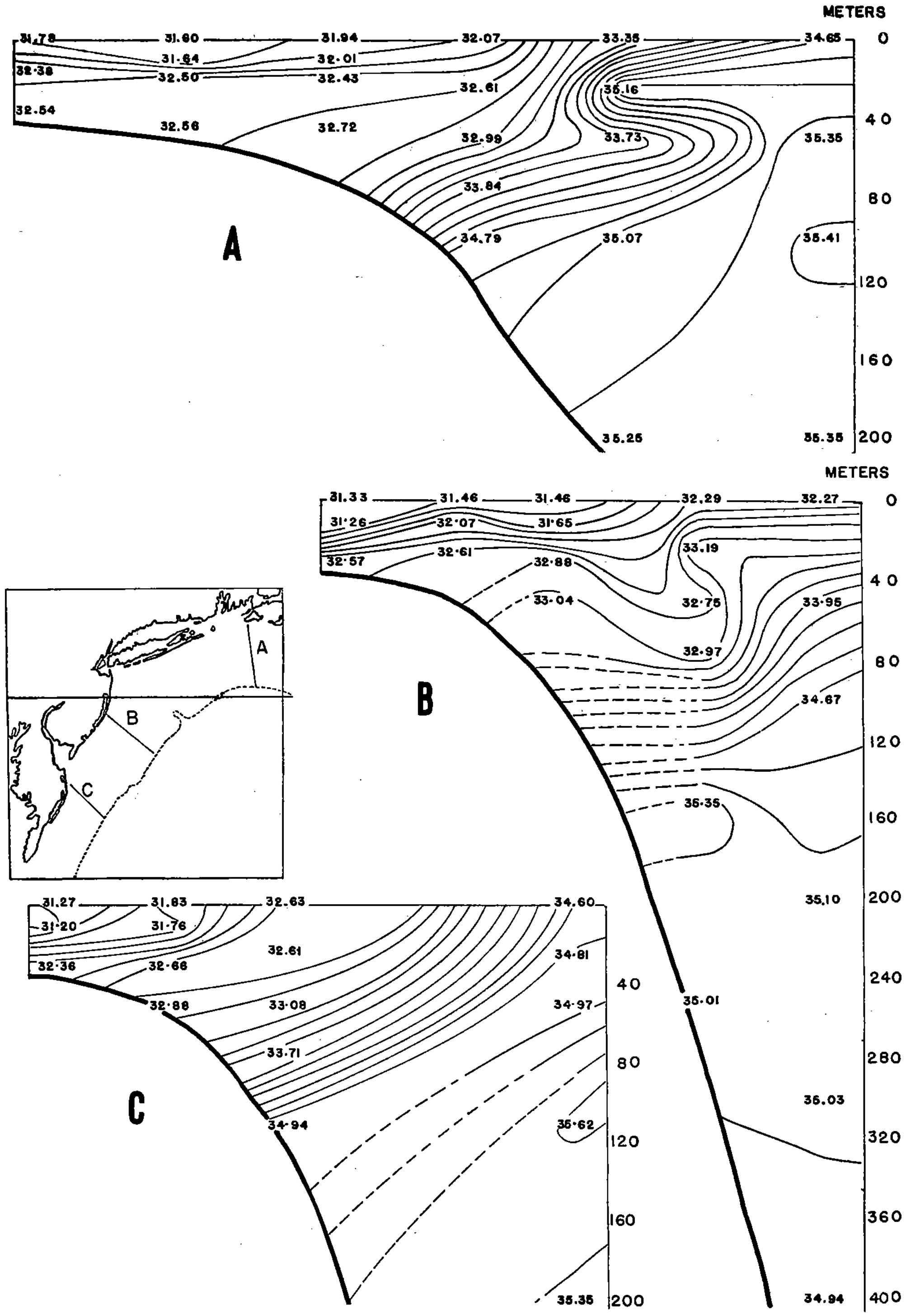


FIG. 36.—Salinity profiles crossing the continental shelf, July 21–28, 1927:—A, off Martha's Vineyard; B, off Atlantic City; C, off Cape May.

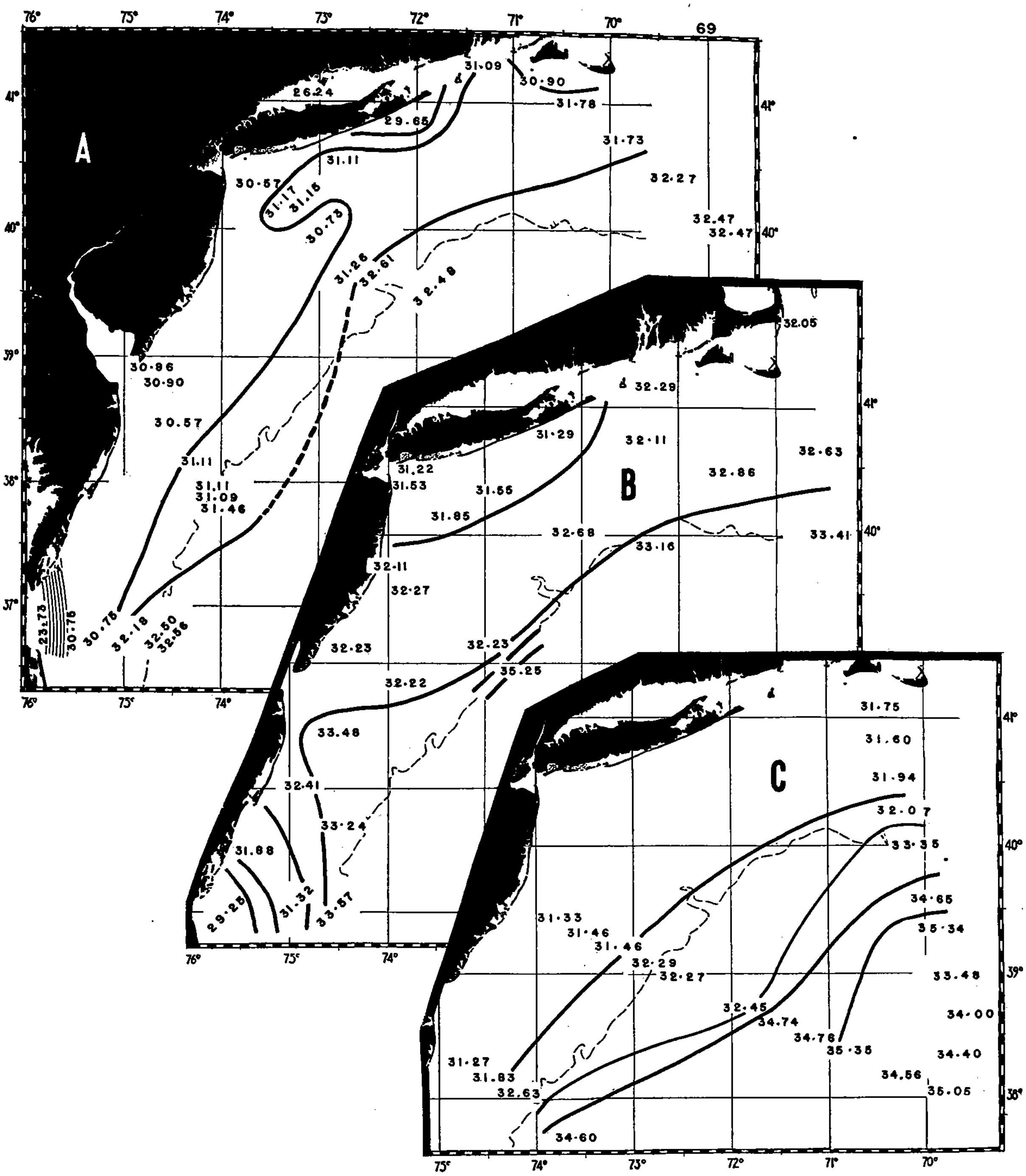

FIG. 37.—Salinity at the surface:—A, July 25–August 26, 1916; B, July 10–August 1, 1913; C, July 20–28, 1927.

Proceeding farther offshore, we find that the isohaline for 33 °/₀₀ may, at the one extreme, lie outside the edge of the continent at this season (Fig. 37), with even the isohaline for 32 °/₀₀ following the outer edge of the shelf, as illustrated by 1916 and 1927. At the other extreme (Fig. 35) the surface may be more saline than 33 °/₀₀, well inside the 100 meter contour along some sectors, and close outside it in others, with 34 °/₀₀ only a few miles farther out.

To the northward of the Cape May profile, it would be highly exceptional for surface water of 35 °/₀₀ to encroach within the continental edge at this season, though its distance out varies widely, between summers of medium or high salinity when it may lie within 10–15 miles of the 200 meter contour, anywhere between the New York and Martha's Vineyard profiles, and summers of the opposite type (e.g., 1916 and 1927, Fig. 37) when it may be 40–70 miles out, along this same sector. But at this time of year, the 35 °/₀₀ isohaline is always to be expected close in to the continental edge off Chesapeake Bay—may even overflow it there, as was the case in July, 1929 (Fig. 35). And, to judge from observations taken at the end of June 1927, pure oceanic surface water, more saline than 36 °/₀₀, is to be expected along the outer edge of the shelf near Cape Hatteras, through the summer, as already described for June (p. 45).

The location of the isohaline for 32 °/₀₀ in the sector to the east of the New York profile, for the years 1930, 1931 and 1932, where observations were taken at close intervals,[33] sufficiently illustrate the prevailing uniformity of distribution, and the general order of magnitude to be expected in the mutual fluctuations of lower and higher salinities, from summer to summer (Fig. 35 C).

Scattering observations for July along steamship tracks to the eastward of New York, in the various years of record (p. 3) have for the most part fallen within the values just outlined. This also applies to the earlier series reported by Dickson (1901), whose charts for the summers of 1896 and 1897 similarly show the isohaline for 32 °/₀₀ as lying close in to Martha's Vineyard with 34 °/₀₀ near the continental edge.[34] Thus it appears that the mean values, for a long series of years, would fall somewhere within the extremes illustrated on the one hand by 1929 (Fig. 35), on the other 1916 and 1927 (Fig. 37), except, perhaps, that the slightly lower values recorded close in to New York for 1928 (p. 56) and 1930, and along the coast on either hand may be more fairly representative of that locality.

Unfortunately the available data throw very little light on alterations in surface salinity during July and August, except to the eastward of the New York profile, for in no one year were general surveys carried out in both of these months.

So far as they go, scattered records suggest that this period is either one of comparative quiescence in this respect over the area as a whole, as it clearly is in the sector to the eastward of New York, or that some slight increase takes place, though with August values generally falling within the limits characteristic of July. Thus in 1897 the isohalines for 32 °/₀₀ and for 34 °/₀₀ occupied approximately the same situations, southward to the offing of Delaware Bay in August as in July (Dickson, 1901). In 1916 the surface over the inner half of the shelf off New York had almost precisely the same salinity on

[33] There are no data farther south, for the month, in those years.

[34] If Libbey's (1891) hydrometer readings can be taken at face value, the surface off southern New England was more saline in July, 1889, than usual, with values averaging about 33.6 °/₀₀ over the inner part of the shelf, about 34 °/₀₀ over the outer part, and about 34.2 °/₀₀ for some miles out beyond the continental edge. But lacking information as to whether the instruments had been standardized, no great stress can be laid on so small a departure. See Clark's (1912) discussion of the early hydrometer readings.

August 26 (31.15 ‰) as on August 1 (31.17 ‰) (Bigelow, 1922, Sta. 10363, 10364). And data collected by the International Council for the Exploration of the Sea combined with our own observations, show that little alteration took place in surface salinity from July to August, along a line New York-Nantucket Lightship, in the years 1923, 1925, 1928, 1931 or 1932. In 1913, on the other hand, water more saline than 34 ‰ moved in over the continental edge to the 120 meter contour line off Martha's Vineyard, between early July and late August. The location of the 34 ‰ isohaline, well inshore, early in August 1908 suggests a similar event in that year.[35] Small increases were also recorded, to the eastward of New York in 1914, 1921, 1922, 1929 and 1930. And average values, for all years combined, on the line New York-Nantucket Lightship show an increase of about 0.4 ‰ for this sector of the shelf as a whole (Fig. 11). Likewise, the lowest steamship record near New York is slightly higher for August than for July (respectively 29.31 ‰ and 27.50 ‰, both for the year 1928).

*Mid-depths.* Little change took place from June to July, in the steepness of the vertical gradient in the eastern part of the area, in 1930 or 1931. But in 1932 the area where the gradient averaged as great as 0.5 ‰ per 20 meters expanded considerably to the eastward between mid-June and mid-July. And comparison of the June state for 1931 and 1932, with July-August charts for 1913, 1916, 1927 and 1929 (Fig. 38) shows that on the whole the mean vertical gradient averages steepest in late summer for salinity, as also for temperature. In summers when surface salinity is relatively low (e.g., 1916 and 1927) all but the outermost zone of the shelf, from the offing of Chesapeake Bay, northward and past the offing of New York, then shows a mean gradient of at least 0.4 ‰–0.5 ‰ per 20 meters of depth. In 1927 this zone continued eastward with undiminished breadth, to the Martha's Vineyard profiles as may also have been the case in 1916 (Fig. 38 A). And even in summers of high surface salinity (e.g., 1929, Fig. 38 C), the area of steep gradient is equally extensive for July in the southern sector of the area, though narrowing abruptly to the eastward, with its limit in this direction not far from the eastern end of Long Island. Years intermediate in surface salinity (e.g., 1913), are also intermediate with respect to vertical gradient (Fig. 38 B).

The years when general surveys were made also show considerable variation in the boundaries of the area of steep gradient to the southward, for while in some summers it occupies all but the outermost zone of the shelf to the southward of Delaware Bay, in other summers it is there confined to the mid-belt, leaving a band of weaker stratification next the land (Fig. 38). Similarly, relatively steep gradients may or may not interrupt the offshore belt of more nearly homogeneous water between latitudes 38° and 39°.

In July, as in May and June, strongest stratification occurs off the source of discharge of landwater; strongest of all (as might be expected) off Chesapeake Bay, where a gradient at the mean rate of 12.25 ‰ per 20 meters of depth was recorded at the 13 meter contour on August 21, 1916 (Fig. 38 A). But gradients of 1 ‰, or more, per 20 meters have been restricted in each summer, to circumscribed pools; the most extensive being shown off the coast of Virginia on the chart for 1913 (Fig. 38 B).

On the other hand, active turbulence maintains a pool of vertically homogeneous water throughout the summer in the region of Nantucket Shoals with regard to salinity, as for temperature (Bigelow, 1933, p. 68), with gradient averaging only about 0.1 ‰

[35] An abnormally high reading of 36.33 ‰ near Nantucket Lightship, August 1, 1908 (Int. Consul. 1910) is probably erroneous.

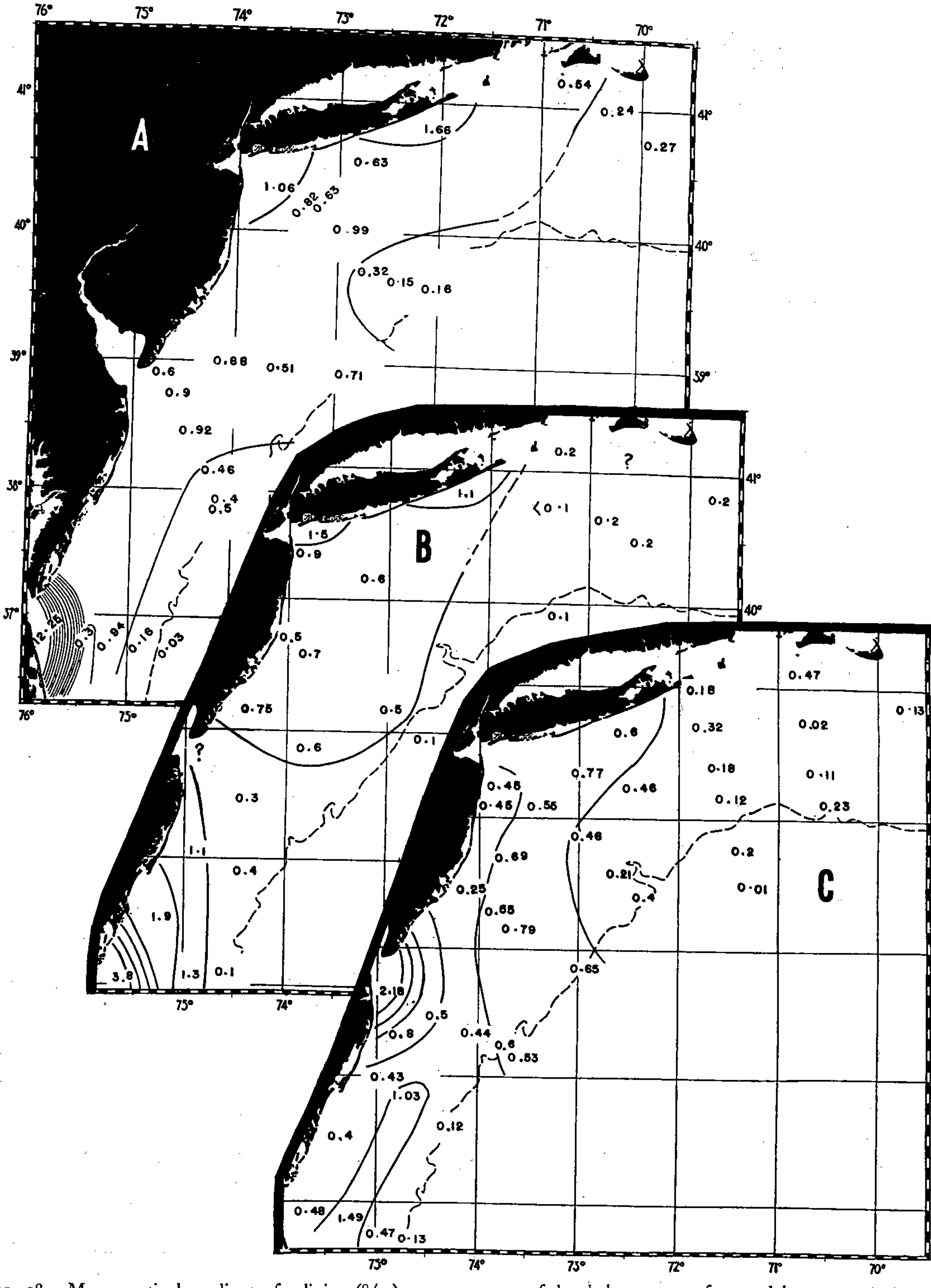

FIG. 38.—Mean vertical gradient of salinity (°/₀₀) per 20 meters of depth between surface and bottom:—A, July 25–August 26, 1916; B, July 10–August 1, 1913; C, July 12–25, 1929. *On account of crowding, the differences in vertical gradient between stations are drawn for each part per mille in chart A rather than each 0.5 °/₀₀.*

per 20 meters of depth between surface and bottom, at twenty August stations in different years, with minimum of 0.02 ‰, and mean of about 0.1 ‰. The data are not sufficient for any correlation to be drawn between steepness of gradient on the shoals and location relative to banks or slopes. This relative homogeneous area of the shoals is bounded offshore by the 60–70 meter contour line, where it gives place to a belt of steeper gradient, along the outer edge of the shelf.

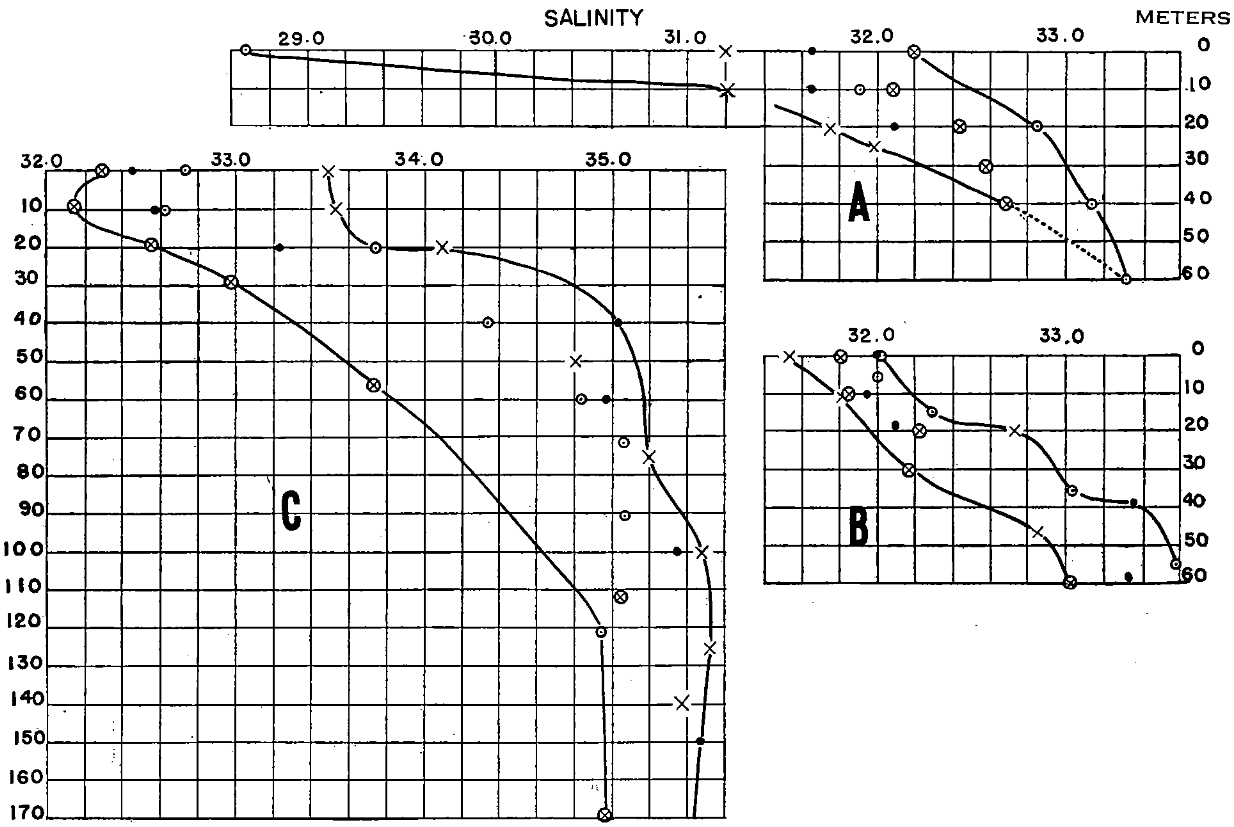


FIG. 39.—Limits of variation in vertical distribution of salinity in July of different years, off New York; ●, 1929; ⊙, 1930; ×, 1931; ⊗, 1932. A, sta. New York I; B, sta. New York III; C, sta. New York V.

Still farther out, along the upper part of the continental slope the mean vertical gradient has averaged small except in the offing of Delaware Bay, where the area of relatively steep gradient extends seaward, out across the continental margin, in some summers (Fig. 38).

In most instances the vertical gradient represents continuous increase in salinity, in midsummer, from surface to bottom, a general rule illustrated not only by individual stations, but equally by the curves showing range of annual variation for representative localities (Figs. 39, 40). But July readings taken at close vertical intervals have shown small vertical reversals of salinity so frequently over the inshore half of the shelf as well as offshore that they cannot be credited either to faulty determination, to confusion of samples, or to other failures of technique. In 1929, for example, two stations midway out off New York (Sta. II, III) showed such reversal; in 1930, one station off Martha's Vineyard (Sta. II) and one off Montauk (Sta. III);[36] in 1931, the inshore half of the Martha's Vineyard profile (Sta. I, II, III) and one station (Sta. I) off Barnegat; in 1932, a notable reversal appeared at station Montauk I. Examples are shown in Figure 41. In such in-

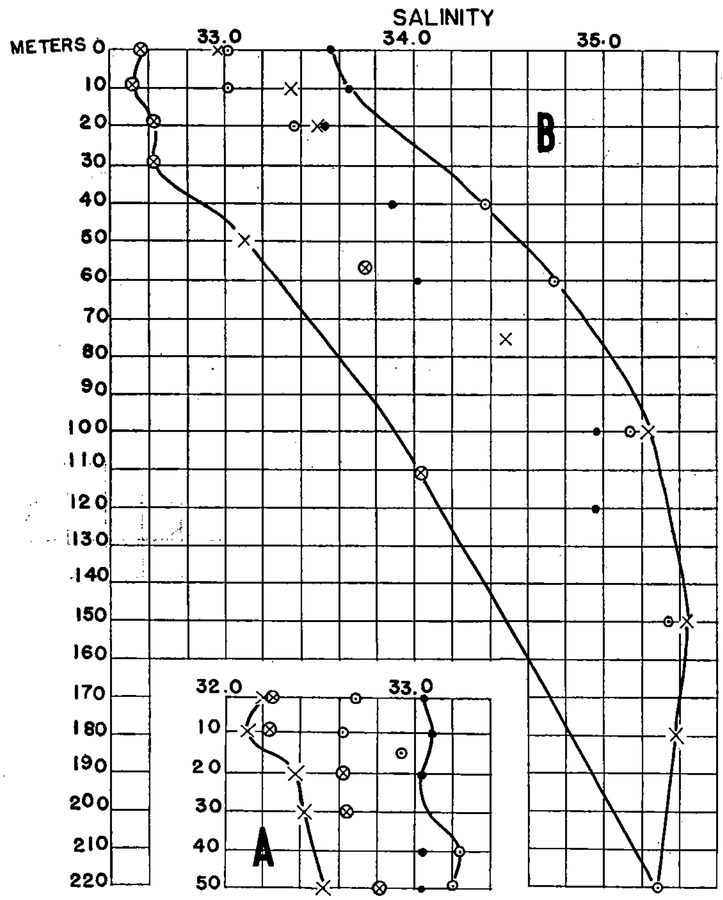


FIG. 40.—Limits of variation in vertical distribution of salinity off Martha's Vineyard in July of different years; ●, 1929; ⊙, 1930; ×, 1931; ⊗, 1932. A, station Martha's Vineyard II; B, station Martha's Vineyard IV.

stances the underlying layer of lower salinity has usually been recorded at the 10–20 meter level, or nearby; only occasionally deeper, as is also the case in June. In one instance (Fig. 42 C) the profile clearly shows interdigitation between inshore and offshore waters as responsible. But as the other profiles are not demonstrative in this respect—nor could be expected to be so, lacking data close in to the land—all that can be stated here is that phenomena of this sort are of frequent occurrence in the coastwise belt in the upper 10–20 meters. But in each instance, yet observed, the underlying stratum of low salinity has been cold enough to make the column vertically stable.

[36] The New York profile for that year shows a similar situation right across the shelf; but in this case the reversal, between surface and 10 meters (a matter of only 0.02 °/₀₀ to 0.04 °/₀₀) is hardly greater than the probable error of the determinations.

Vertical reversals of salinity also occur along the edge of the continent, or to seaward of it in mid- and late-summer (Fig. 41 B), as at other times of year, resulting from interdigitations between shelf and slope waters such as are described above for February, May and June (pp. 10, 40, 50). Striking examples for July appear on the Martha's Vineyard profiles for 1927 and 1931 (Fig. 43 A); on the Cape May and Winterquarter profiles for 1929 (Fig. 42 C); and on the Chesapeake Bay profile for 1913 (Fig. 43 D). In at least one instance (Vineyard profile, 1931) the serial observations, at the continental edge, cut

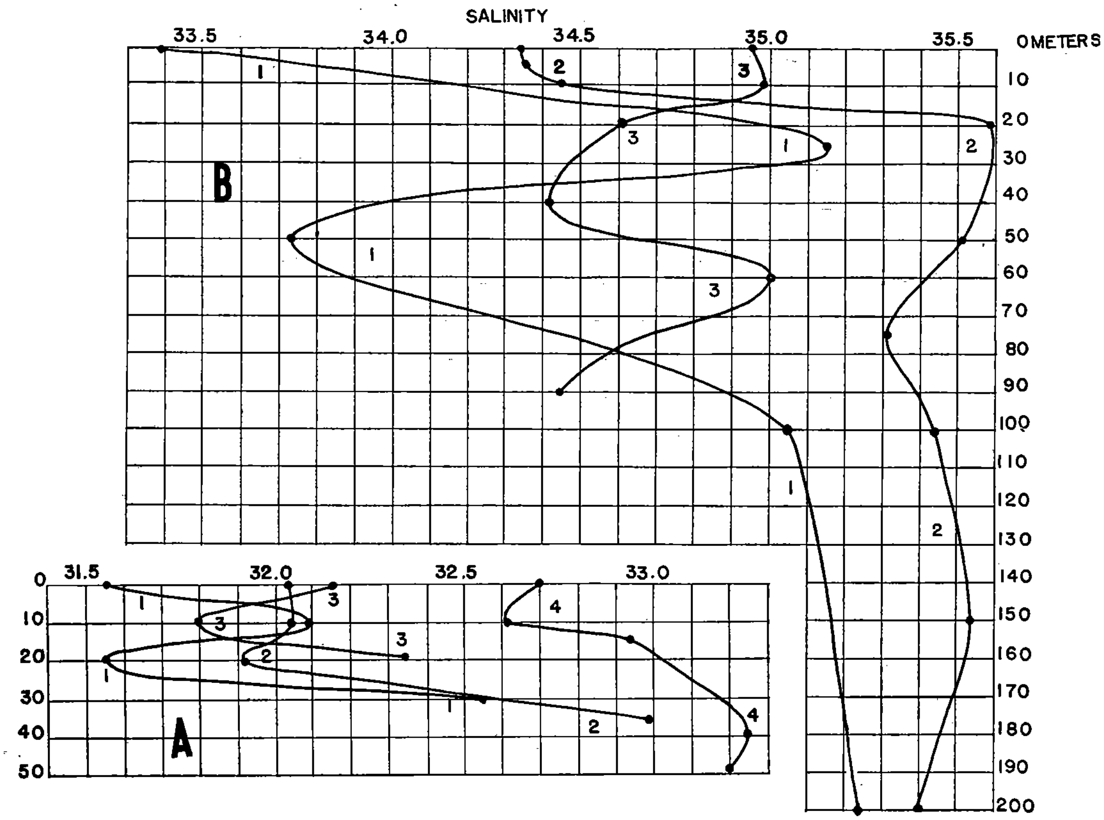


FIG. 41.—Vertical distribution of salinity at representative stations showing vertical reversals in summer:—A, inshore:—(1) sta. Shinnecock I, July 18, 1932; (2) sta. New York II, July 22, 1929; (3) sta. Montauk I, July 16, 1932; (4) sta. Martha's Vineyard II, July 14, 1930. B, offshore:—(1) sta. Martha's Vineyard V, July 28, 1927; (2) sta. Martha's Vineyard V, July 13, 1931; (3) sta. Winterquarter III, July 18, 1929.

through five successive layers, alternately lower, higher, lower, higher and lower in salinity, between surface and bottom, in a total depth of 175 meters, illustrating the complexity that may temporarily exist. Most of the July profiles that have been run seaward far enough to reach water of 35 °/₀₀, and downward to a depth as great as 200 meters have indeed, shown something of this sort; usually with the highest salinity approaching the slope most closely at the 100–150 meter level, though sometimes much closer to the surface (Figs. 42 A, B; 40).

In July, as in June (and for the reason pointed out on page 50), salinity runs counter to temperature in this respect, instead of parallel as is the case in the cold months of the

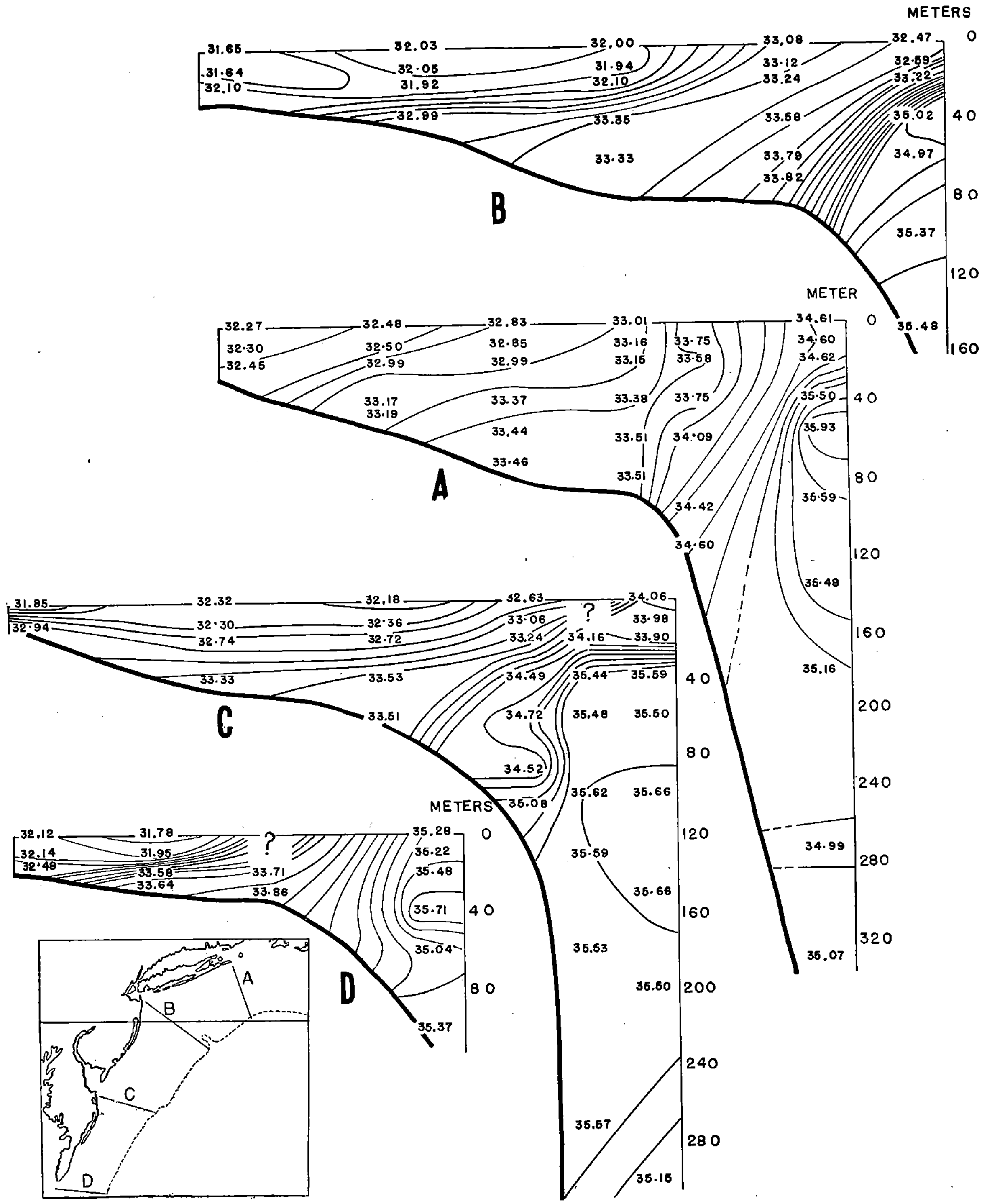

FIG. 42.—Salinity profiles crossing the continental shelf, July 18–24, 1929:—A, off Montauk; B, off New York; C, off Cape May; D, off Chesapeake Bay.

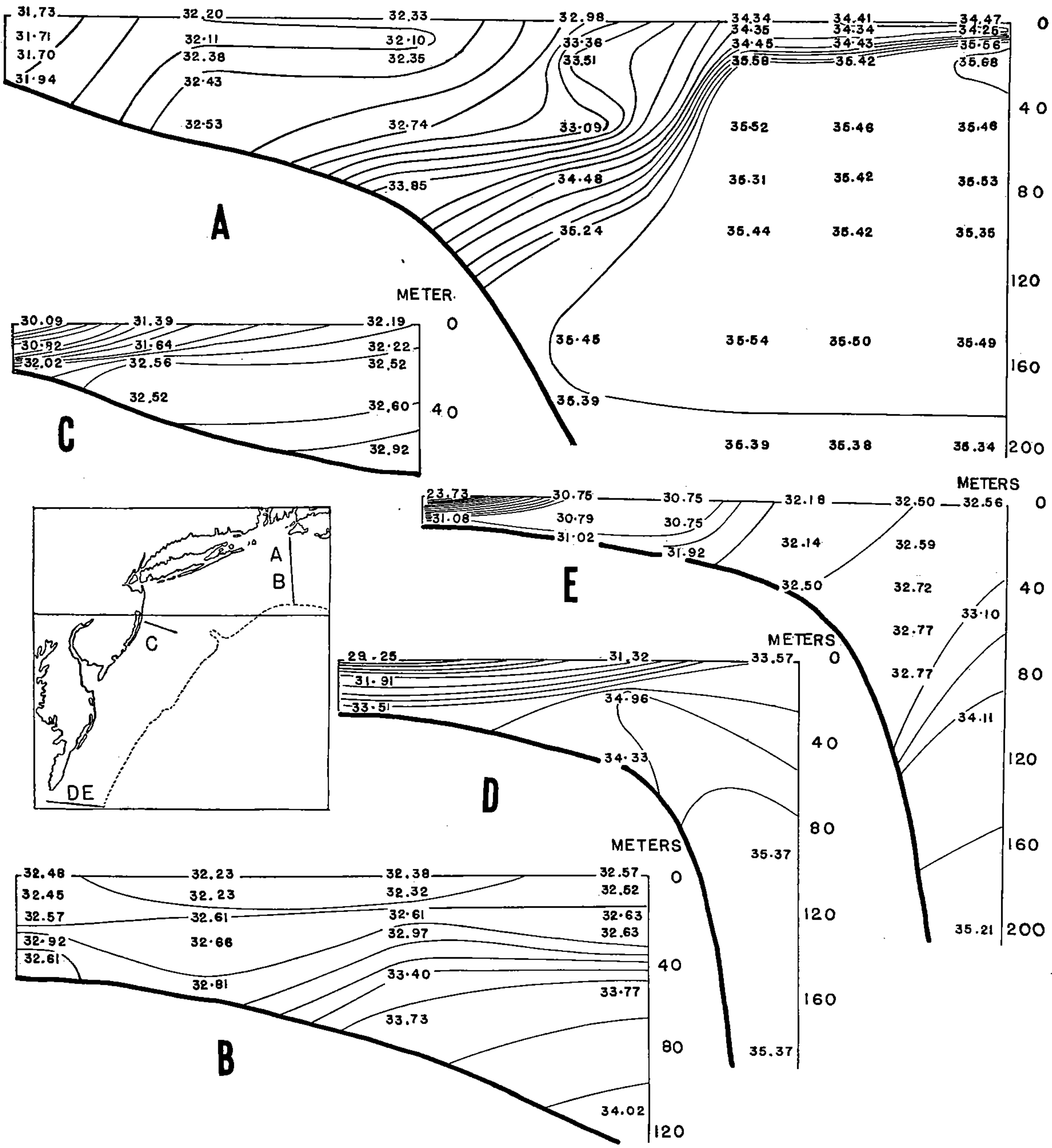


FIG. 43.—Salinity profiles crossing the continental shelf:—A, off Martha's Vineyard, July 13–14, 1931; B, off Martha's Vineyard, July 19–20, 1932; C, off Barnegat, New Jersey, July 12, 1931; D, off Chesapeake Bay, July 24–29, 1913; E, off Chesapeake Bay, August 21–22, 1916. *Because of crowding, isohalines on profiles D and E are given for every 0.5 °/₀₀ only.*

year. It is unfortunate that in the particular cases noted above, we lack the corresponding observations for June that would have shown how rapidly such situations may develop. Conversely, data for July are lacking for the particular years and profiles where vertical reversals were recorded in June (p. 50). However, the considerable variation from profile to profile, in July, as well as in other months, is evidence that they are short-lived, or in a state of constant alteration—as might, indeed, be expected.

Apart from reversals of the sorts just described, the upper stratum of water, over the shelf, is on the whole more nearly homogeneous than the mid-stratum in July. But the situation in this respect is much less regular for salinity than for temperature, for while some profiles may show a comparatively homogeneous surface layer 10–20 meters thick, extending for a considerable distance across the shelf (Fig. 43 B); others show transition within a few miles, between stations of this type and others, where a vertical gradient (and sometimes a very steep one) may commence right at the surface (e.g., New York profile, 1931; Chesapeake Bay profile, 1916) while, more rarely, (e.g., Chesapeake profile, 1913; Barnegat profile, 1931, Fig. 43 C, D) this latter state has characterized the whole breadth of the profile.

In spite of the fact that the average difference in salinity, between surface and bottom increases from June through July (pp. 60–62), profiles for the latter month do not suggest any general strengthening of zones of convergence, nor, in fact, any other basic alteration in the distributional pattern. In July, as in June, individual profiles may show the two convergences, already described (p. 49), or one of them, or neither; or the vertical gradient may be distributed irregularly. Examples of such variation are shown in Figures 42–44.

The regional contrast (p. 50) between the extreme eastern part of the area (Martha's Vineyard profile), where the vertical gradient continues relatively small through the summer, and the shelf as a whole to the south and west, is correspondingly reflected in the fact that the most abrupt transition on any of the Martha's Vineyard profiles, out to the 200 meter contour, has been only about 0.3 ‰ per ten meters; contrasting with a maximum of about 1.00 ‰ per ten meters on the profile next to the west (Montauk, July, 1932) at this same season.

The situation with regard to development of such layers is even more variable in July than in June, both regionally and from year to year on given profiles. Off Chesapeake Bay, for example, in a summer (e.g., 1913) when water more saline than 34.5 ‰ lies well in over the shelf, the transition between it and the coastal water may be condensed into a single well-developed convergence (Fig. 43 D). But in other summers (e.g., 1916), when slope water lies far out, and when discharge from the bay continues in large volume until late in the summer, as many as three such bands may appear on that same profile (Fig. 43 E); while in still other years, there may be two such bands, i.e., the more generally typical state (e.g., 1929, Fig. 42 D). Considerable, if less striking differences also appear from year to year on the more northerly profiles. Off Cape May, for example, the bottom along the outer edge of the shelf may be overlaid by a considerable mass of relatively homogeneous water in some years (e.g., 1916), with abrupt transition both offshore, and toward the surface, while in other summers (e.g., 1927, Fig. 36 C and 1929, Fig. 42 C) the homogeneous bottom band may lie considerably farther in on the slope, with corresponding differences in the courses of the isohalines. Off New York, again, the two convergences just mentioned may both be well developed, enclosing a relatively homogeneous mass extending from surface to bottom (1931, Fig. 44 B). At the other

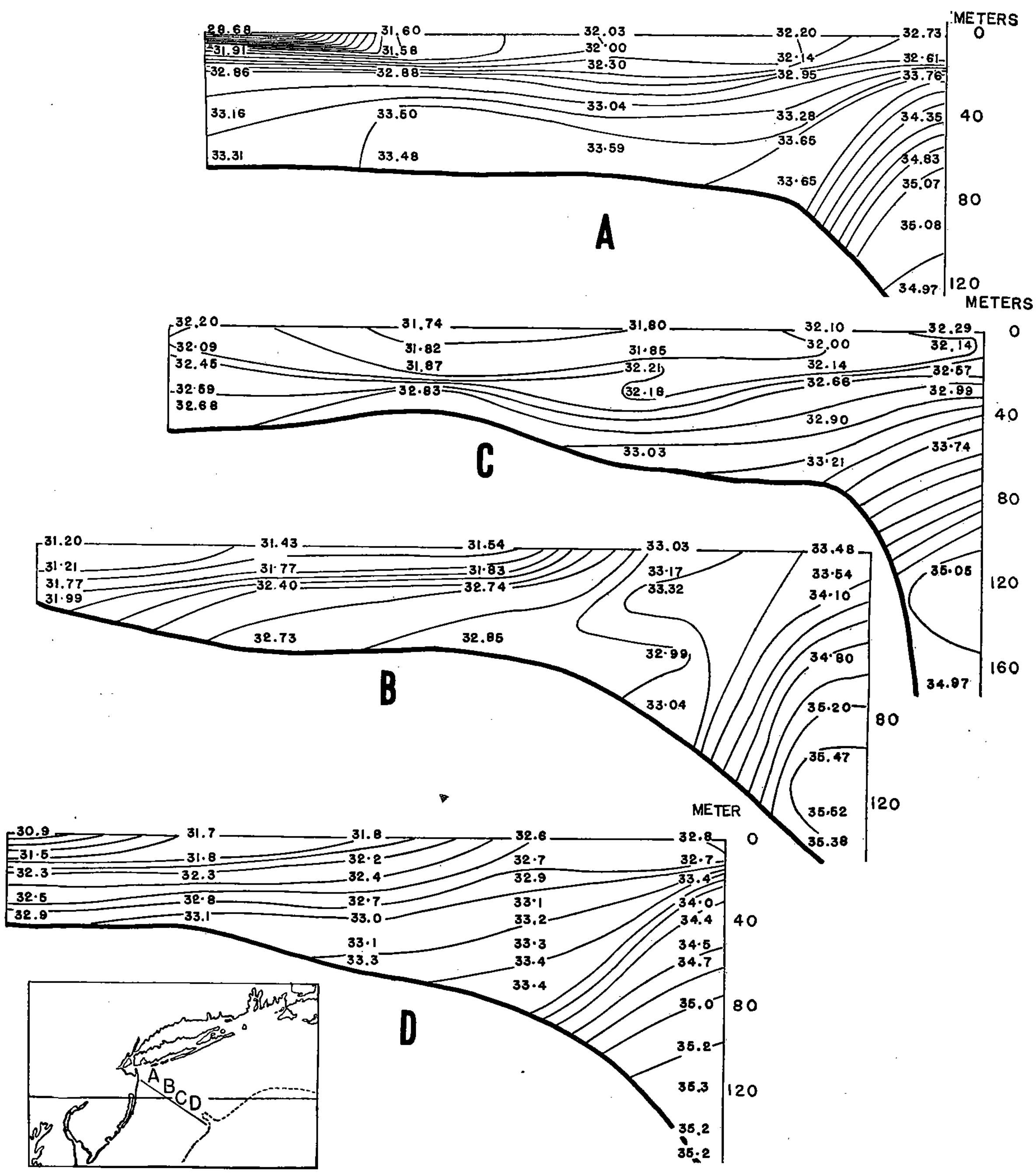


FIG. 44.—Salinity profiles crossing the continental shelf off New York:—A, July 11–12, 1930; B, July 11, 1931; C, July 18–19, 1932; D, mean, for July, for years 1929, 1930, 1931 and 1932, combined.

extreme, the gradient may be more continuously, though irregularly distributed between surface and bottom right across the shelf (Fig. 44 C, 1932), while other years show various intermediates. The more easterly profiles also show similar year to year fluctuations, better illustrated graphically than verbally (Figs. 42–44).

It is in July, also, that the most abrupt transitions have been recorded in salinity, not only close inshore but midway out on the shelf as well, or even far offshore. Extreme examples of the first of these categories were at the mouth of Chesapeake Bay, August 21, 1916 (Fig. 43 E), and off New York, July 12, 1930 (Fig. 44 A), where vertical ranges of $>7.00\,^{\circ}/_{\circ\circ}$ and $>3.00\,^{\circ}/_{\circ\circ}$ respectively were recorded between the surface and the 12-meter level. Midway out on the shelf, the steepest gradient so far recorded has been $3.1\,^{\circ}/_{\circ\circ}$ between the surface and 18 meters, off Chesapeake Bay, July 29, 1913 (Fig. 43 D); while over the continental slope, off Martha's Vineyard, on July 13–14, 1931, the salinity rose by $1.3\,^{\circ}/_{\circ\circ}$, in a vertical distance of only 6 meters (4 meter to 10 meter levels, Fig. 43 A). But abrupt transition zones, such as those just described, are invariably limited to small areas—in no instance (for salinity) has such a zone extended the whole distance across the shelf, as is so usually the case for temperature at this season. And the difference in vertical distribution between these two characters of the water in this respect is made expecially striking by comparison of mean profiles off New York (cf. Fig. 44 D with Bigelow, 1933, Fig. 43 A), for combination of the several years' data smooths out the yearly irregularities.

The contrast between temperature and salinity, with regard to the relative homogeneity of the surface stratum is noted above (p. 67). Similarly, the bottom stratum over the outer half of the shelf, is more nearly homogeneous in temperature than it is in salinity (Cf., for example, Montauk profile, July 23–24, 1929, Fig. 42 A, with Bigelow, 1933, Fig. 42 B).

The profiles that have been run out across the continental slope represent summers of relatively high salinity (1929) as well as of relatively low (1916, 1927); hence may be taken as representative of the extremes to be expected at that season in any but an exceptional year. On this basis, it appears that the upper part of the slope is normally skirted in late summer (as in late spring) by a belt that is much more homogeneous, and much more uniform, than the inshore waters, with values of $>35\,^{\circ}/_{\circ\circ}$ usually extending downward to a depth varying between 300 and 800 meters (p. 70), below which salinities fall to the slightly lower value characteristic of North Atlantic abyssal water. And the fact that $35\,^{\circ}/_{\circ\circ}$ water was in contact with the slope in July 1927, following a May when this had not been the case, suggests that in years when slope water lies farther out during the preceding months, it tends to press inshore toward the continental edge in summer.

On the more northerly profiles, a less saline surface stratum has invariably extended seaward, out beyond the 1000 meter line above the $35\,^{\circ}/_{\circ\circ}$ water-mass, whereas the latter may occupy the whole water column as far in as the 100 meter-contour on the southerly profiles (Fig. 42 D). The highest salinities ($35.4\,^{\circ}/_{\circ\circ}$–$35.7\,^{\circ}/_{\circ\circ}$) along the belt included between the 200 meter and 1200 meter contours, between the Chesapeake Bay and Martha's Vineyard profiles have invariably lain at some intermediate level, usually between depths of 20 meters and 120 meters (Fig. 43 A, B).

In 1927, when oceanic water of $36\,^{\circ}/_{\circ\circ}$ was in on the shelf near Cape Hatteras at the end of June,[37] its inshore edge was encountered about 140 miles out from the conti-

[37] And presumably so, through the summer (p. 59).

nental edge off Cape May in mid-July, bounded by a convergence extending nearly vertically from the surface, down to a depth of more than 400 meters (Iselin, 1930, Fig. 6). But while it lay about the same distance out, off the eastern end of Georges Bank, near longitude 64°, intermediate profiles extending 160 miles from the continental edge off Atlantic City, and out for 120 miles off Martha's Vineyard failed to reach it at all. In July 1928, the New York profile crossed a band of 36 ‰ water some 25 miles broad at the 50–250 meter level, only 60 miles out from the continental edge, a second even narrower and thinner band with its axis at 50 meters, about 135 miles out, which again gave place to lower values still farther out. And in July 1914, 36 ‰ water lay within some 25 miles of the continental edge, abreast the western end of Georges Bank (Bigelow, 1927, Figs. 145, 156). The most that can be said, from such scattered observations, is that the inshore boundary of >36 ‰ water, which (judging from conditions in June, described above) is inshore of the continental edge off Cape Hatteras, and not far from it off Chesapeake Bay, tends thence to swing offshore, across the suboceanic bight that has its apex off New York. Whether it is characteristic of summer, for this boundary to again approach the continental edge more closely off Georges Bank (as was the case in 1914), or whether this happens only in particular summers, is an open question. But it is at least clear that the triangle between this sector of the continental slope and the inner edge of oceanic water is a region of great oceanographic interest. (See footnote 35, p. 60.)

*Bottom.* It is probable that, in most years, the bottom salinity for July falls within the limits illustrated by 1929 on the one hand, by 1916 and 1927 on the other (Fig. 45 A, B); the first of these summers having been characterized by notably high salinities (p. 29), the last two by low. Judging from this, the bottom water across all but the outermost zone of the shelf may, on the one hand, be less saline than 33 ‰ at this season with values as low as 31 ‰–31.6 ‰ along the 20–25 meter belt; on the other hand the isohaline for 33 ‰ may lie close inshore, with values of 32.5 ‰ (or higher) close to the bottom in depths as small as 20–30 meters. In 1930, a bottom value of 33.12 ‰ was, indeed, recorded, off Barnegat, at a depth of only 25 meters; 32.9 ‰ and 33.2 ‰ over the 20 meter line off the mouth of Delaware Bay in 1929. Closer in still, and especially off the mouth of the two great bays, even wider fluctuations are to be expected, but only scattering data are yet available.

With so short an observational series showing so wide an annual range, it is probable that a more representative picture of normal distribution results from calculation of mean values for the several years combined (Fig. 45 C), than from any given year. On this basis, it appears that in late summer, animals living on bottom are subject to annual fluctuations of 0.5 ‰–1.5 ‰ out to the 100 meter line, in the northern part of the area; fluctuations of 1.00 ‰–2.4 ‰ out at least to the 150 meter line off Chesapeake Bay. Contrasting with this wide yearly variability on the shelf, the bottom water on the upper part of the continental slope, from 150 meters downward, off Chesapeake Bay, and from 100 meters downward farther north and east, has proved remarkably constant in salinity from year to year, with all recorded values falling within the range of 35 ‰–35.4 ‰; usually 35.1 ‰–35.3 ‰. Available data do not suggest bottom values much higher than this, anywhere down this sector of the slope.

The depth of the lower boundary of bottom water of 35 ‰ varies widely at this season. On the one hand, it has been found to give place to slightly lower values (34.9 ‰) at as shallow a depth as 250 meters, as was the case on the Montauk profile of July, 1929 (Fig. 42 A), or even at about 150 meters (New York profile, August 2, 1916). More

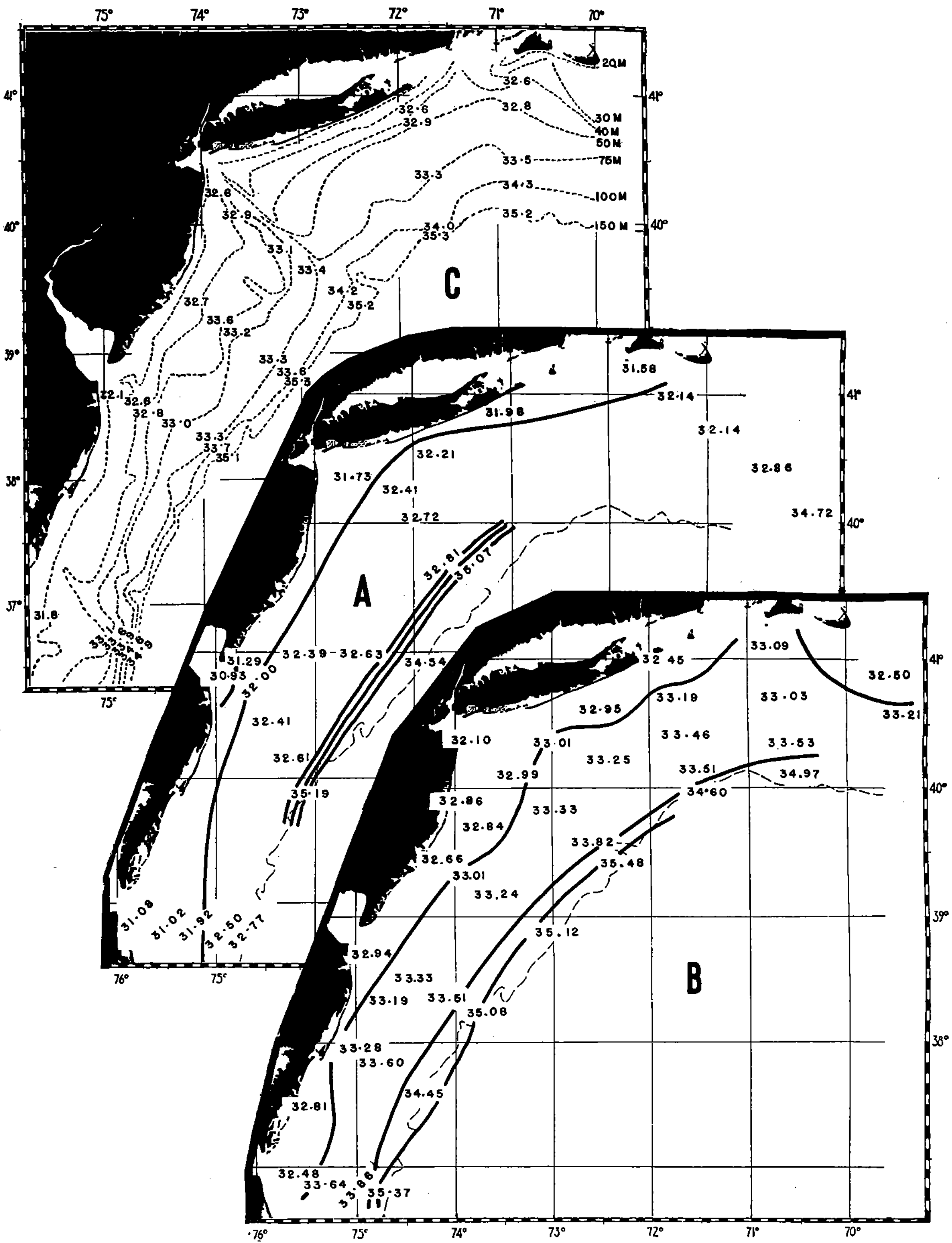


FIG. 45.—Salinity close to the bottom, out to the 200 meter contour, July–August:—A, July 25–August 26, 1916; B, July 12–25, 1929; C, mean bottom values scaled from profiles, for July–August, all years combined, at depths of 20, 30, 40, 50, 75, 100 and 150 meters (contours indicated by broken lines).

often it lies at 350–400 meters, as on the New York profile of 1913, the Chesapeake and New York profiles of 1916, Cape May and Atlantic City profiles of 1927 (Fig. 36 B, C). And occasionally it is deeper, as on the Winterquarter profile for 1916 (450–500 M.), the Barnegat profile for 1913 (about 500 M.), the Martha's Vineyard profile for 1927 (>800 M.), and the New York profile for July, 1928 (450–500 M.) The stations have not been spaced closely enough to show what order exists in these fluctuations—whether secular, regional, or a combination of the two. However, the gradient down the slope is in any case very small, contrasted with the very abrupt transition often recorded in across the continental edge.

Comparable data on seasonal alterations in bottom salinity from mid-June to mid-July are confined to the eastern profiles (New York to Martha's Vineyard, in most cases out to the 100 meter line only) for the years 1930, 1931 and 1932. In the first of these summers a general increase of 0.2 ‰–0.4 ‰ took place from the one month to the other, with only two stations showing small decreases. In 1931 the change was of the reverse order (i.e., decrease) except close in to New York on the one hand and at the outermost stations off Montauk and Martha's Vineyard on the other, where increases were registered. In 1932, bottom salinities decreased slightly in the inshore belt off New York and off Martha's Vineyard, but increased elsewhere.

Thus the bottom salinity of the eastern part of the area may either increase, or decrease slightly in any individual year during the first two months of summer. But it is probable that mean values, for a considerable series of years, would not show any considerable change in either direction that could be described as part of the normal seasonal cycle. It seems that this also applies in general as far south as the offing of Delaware Bay, for the mean bottom values at different depths on the Atlantic City and Cape May profiles, for July of the years 1931, 1916, 1927 and 1929,[38] fall well within the June extremes for these same profiles for 1930, 1931 and 1932.[39] On the other hand the bottom right across the Winterquarter profile was 0.2 ‰–0.5 ‰ more saline in July of 1929, than in June either of 1931 or 1932, while mean values along the 30–40 meter belt for July of 1913, 1916 and 1929 (Fig. 45 C) were 0.4 ‰–0.7 ‰ higher off Chesapeake Bay in July of 1913, 1916 and 1929 than in June, 1931, suggesting that some increase may take place from June through July in bottom salinity to the southward of Delaware Bay. But if this increase be an annual event, it is not so great but that bottom salinities may be lower there in July or even August of some years (e.g., 1916) than in June of others, e.g., 1931.[40]

It is worth noting, in passing, that bottom salinities for July and August are about the same on Nantucket Shoals, at equal depths, as on the smoother ground to the west. This east-west unity is illustrated by the agreement between approximate mean values, for all years combined, on the Martha's Vineyard profile and at various localities on the shoals for July and August of 1928, 1930, 1931 and 1932,[41] tabulated below.

| Meters | Martha's Vineyard Profile | Nantucket Shoals |
|---|---|---|
| 20 | — | 32.0 |
| 30 | — | 32.3 |
| 40 | 32.6 | 32.5 |
| 50 | 32.8 | 32.8 |

[38] 1916 was a summer of notably low, 1929 of relatively high, 1913 of medium salinity.
[39] There are no July data on these profiles for the latter group of years.
[40] Chesapeake profile, 25–30 meters; 32.7 ‰ on June 16, 1931, 31.9 ‰ on August 21, 1916.
[41] Scaled from a diagram of bottom readings at all "Shoals" stations plotted against depth.

Data for the shoals have been too scattering to show to what extent Gulf of Maine upwellings are made recognizable there by increase in salinity of the bottom water, as they clearly are by low temperature (Bigelow, 1933, p. 77).

## Autumn to Winter

*Surface.* In the only year (1932) when a general survey was made in September, a considerable increase had already taken place in surface salinity since July, the area less saline than 32 °/₀₀ in the offing of New York having contracted to a small isolated pool, and the isohaline for 33 °/₀₀ having pressed in over the outer zone of the shelf (Fig. 46 A). To the southward, a general equalization, across the shelf, had meantime concealed all localized evidences of the outflow from Delaware and Chesapeake Bays, values >33 °/₀₀ now reaching right into the mouth of the latter in place of the area of low salinity that often exists there in July (Fig. 37 A, B). This corresponds to the fact that the mean rate of discharge from the Connecticut, Delaware and Susquehanna rivers in each case declined somewhat from June or July to September of that year (U. S. Geological Survey, 1934); though the Hudson showed little monthly change.

Steamship data for the sector to the east of New York (Fig. 11), for all the years combined, also show a mean increase of about 0.7 °/₀₀ from July and of about 0.3 °/₀₀ from August to September, usually with the isohaline for 34 °/₀₀ shifting its location definitely shoreward. In some years (e.g., 1924, 1927, 1930, 1931), however, the surface may show little change in salinity from August to September at least in this sector.

In some years, surface salinities rise only slightly above the summer minimum by October. Such was the case in 1931, when the isohaline for 32 °/₀₀ had shifted only slightly inshore by the middle of that month, with the isohaline for 33 °/₀₀ still encroaching but slightly within the continental edge (Fig. 46 B). The year 1915 seems also to have been of this type, for surface values on the Martha's Vineyard profile, for that October, were about the same (Bigelow, 1917, stations 10332–34) as in October 1931. But steamship data to the eastward of New York have in general ranged slightly higher in October (average about 33 °/₀₀) than in September (average about 32.9 °/₀₀), with values <32 °/₀₀ confined to the close vicinity of land, near New York harbor, usually with the isohaline for 33 °/₀₀ well in on the shelf, and with 35 °/₀₀ twice recorded inside the 100 meter line off Nantucket (years 1911 and 1920).

In 1931, October isohalines failed to show any definite expansions of very low salinity off rivers or bays. And the data for 1916 (Fig. 46 C) show that this state is reached off Chesapeake Bay before mid-November, at latest, with considerable increase[42] above the summer minimum thence northward past Delaware Bay, even in a year when summer salinities are abnormally low. Some increase in surface salinity from October through November seems characteristic for the immediate vicinity of the coast near New York, where November readings have all been higher than 32 °/₀₀, whereas in October a considerable area there may be less saline than 32 °/₀₀ (Fig. 46 B). And the minimum recorded value near New York is again about 0.2 °/₀₀ higher for December (±32.2 °/₀₀) than for November; with only two out of forty-seven December readings falling below 32.5 °/₀₀ there.

Farther out on the shelf, however, in the eastern sector,[43] average values, for all years have been about the same (±33.00 °/₀₀) for November as for October, showing

[42] Increase of 0.6 °/₀₀–2.0 °/₀₀ between August and November of 1916.
[43] Steamship records on line New York-Nantucket Lightship.

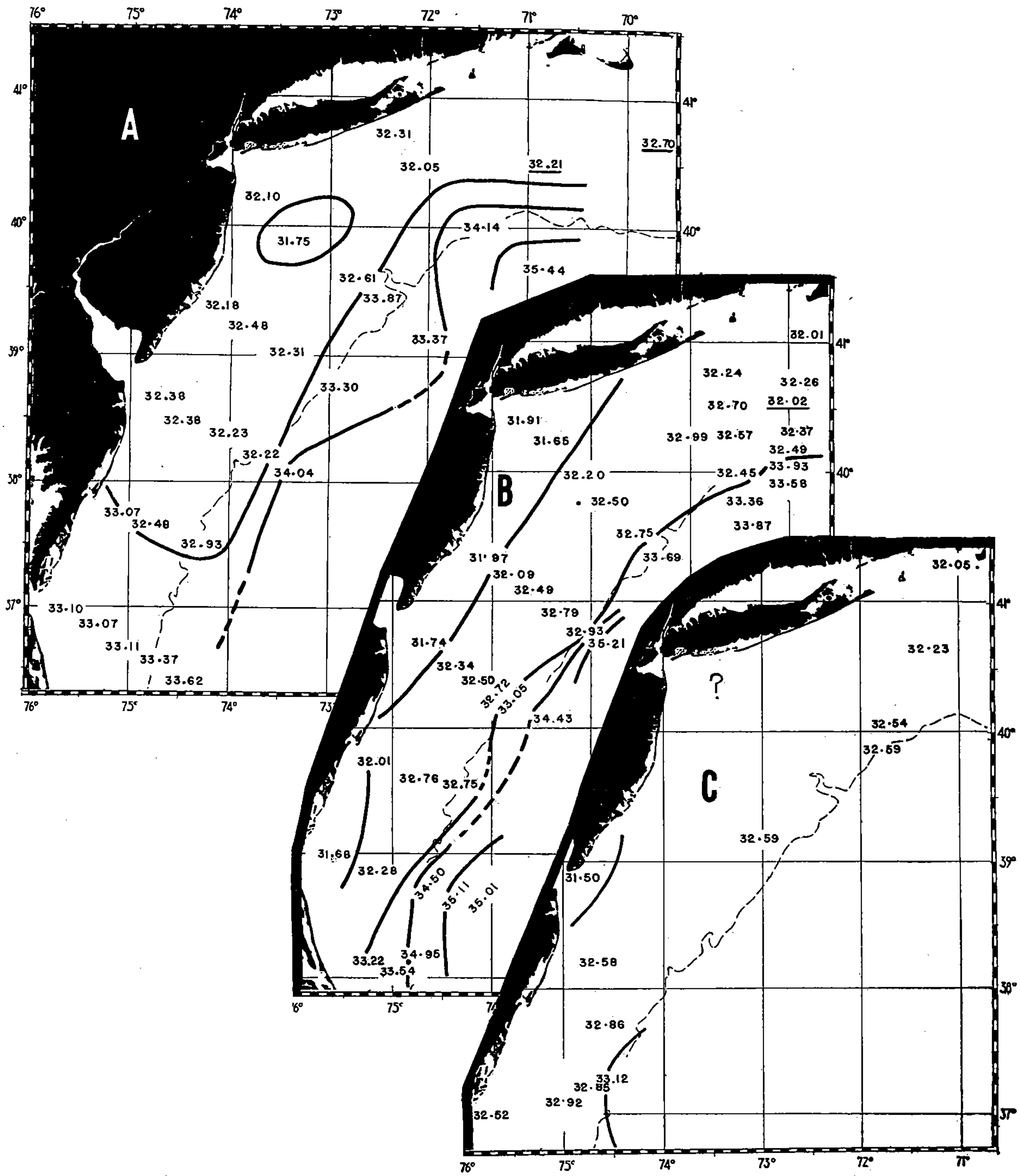

FIG. 46.—Salinity at the surface:—A, September 3–10, 1932; B, October 19–28, 1931; C, November 10–17, 1916.

that the average trend is so small, in either direction, at this season, that it is entirely masked by the yearly variations. And how wide the latter may be, appears from the contrast between 1916 (Fig. 46 C), when the isohaline for 33 °/₀₀ had not encroached at all on the shelf by mid-November, between the offings of Montauk and of Chesapeake Bay, and 1921, 1928 (Fig. 47 A) and 1932, when this isohaline lay well in, at least in the eastern sector,[44] and when 35 °/₀₀ was close to the continental edge; as it also was off Chesapeake Bay at the end of the month, in 1932.[45] Surface salinities, in the eastern sector may, in fact, be higher in October of some years than in November of others. Among the other years of record, 1930 and 1932 showed 33 °/₀₀ even closer to land, whereas November distribution in the eastern sector was of much the same type in 1912, 1927 and 1931 as in 1916 (Fig. 46 C).

The fact that mean values, in the sector to the east of New York, for November (±33 °/₀₀), agree closely with December (mean, ±32.9 °/₀₀)[46] suggests continued quiescence there, through the first month of winter. And this is corroborated by the fact that the data for individual years show only slight changes in either direction, from the one month to the next, at corresponding locations. But some encroachment of offshore water may be more characteristic of early winter than would appear from the preceding, for our only general survey for December (1932, Fig. 47 B) showed water of 35 °/₀₀ farther in over the continental edge off Cape May and Martha's Vineyard than it has been found at any other time of year, and with salinities higher than 34 °/₀₀ all along the outer zone of the shelf within this sector.

No general surveys of the region as a whole have been made in January, but records on the line New York-Nantucket Lightship yield a slightly higher average for that month (33.2 °/₀₀) than for December (32.9 °/₀₀); also a slightly higher minimum value (±32.5 °/₀₀, as against 32.2 °/₀₀). This, with the facts that the values there, for 1929, were slightly higher in January than in February,[47] that those for December, 1931-January, 1932, about equalled the February values for 1930, and that the surface off Chesapeake Bay for January had almost precisely the same salinity in 1914 as in 1916,[48] indicate that surface salinity normally reaches its annual maximum by mid-winter.

No great alteration is to be expected thereafter until the next vernal freshening, except in the immediate vicinity of the mouth of Chesapeake Bay where very low values (29.00 °/₀₀–30.00 °/₀₀) recorded in January, both of 1914 and of 1916 (Fig. 47 C) show that temporary fans of low salinity may develop, as at other times of year. On the other hand it is worth noting that there is nothing in the record to suggest any notable encroachment of slope water, inshore in January or February.

*Mid-depths*. Autumnal salting of the surface tends to decrease the difference, in salinity, between surface and bottom, that has built up during spring and early summer (see below, p. 78). In 1932, the area where mean vertical gradient was as great as 0.4 °/₀₀ per 20 meters of depth was already much less extensive by the first week of September (Fig. 48 A) than it usually is in summer (p. 60, Fig. 38), being now confined to the coastal belt from New York to Chesapeake Bay, and to one station along the continental

[44] No observations were made farther south in November of those two years.

[45] On November 10, 1932, a reading of 35.99 °/₀₀ was recorded, near the 100 meter contour, south of Nantucket (Int. Conseil 1933).

[46] Fifty-nine readings for November, 47 for December, in different years, mostly along the line New York–Nantucket Lightship.

[47] No comparative data for January–February of other years.

[48] 33 °/₀₀ midway out on the shelf, 34 °/₀₀ just inside the continental edge; 35 °/₀₀ some 20 miles out and 36 °/₀₀ some 50–60 miles farther out.

edge. And while the autumnal schedule was more tardy in 1931 (p. 73), it was only here and there along the continental edge, and at one station off the coast of North Carolina that the vertical gradient still averaged as steep as 0.4 °/₀₀ per 20 meters by the last week of that October (Fig. 48 B). By the end of December 1932, the mean gradient

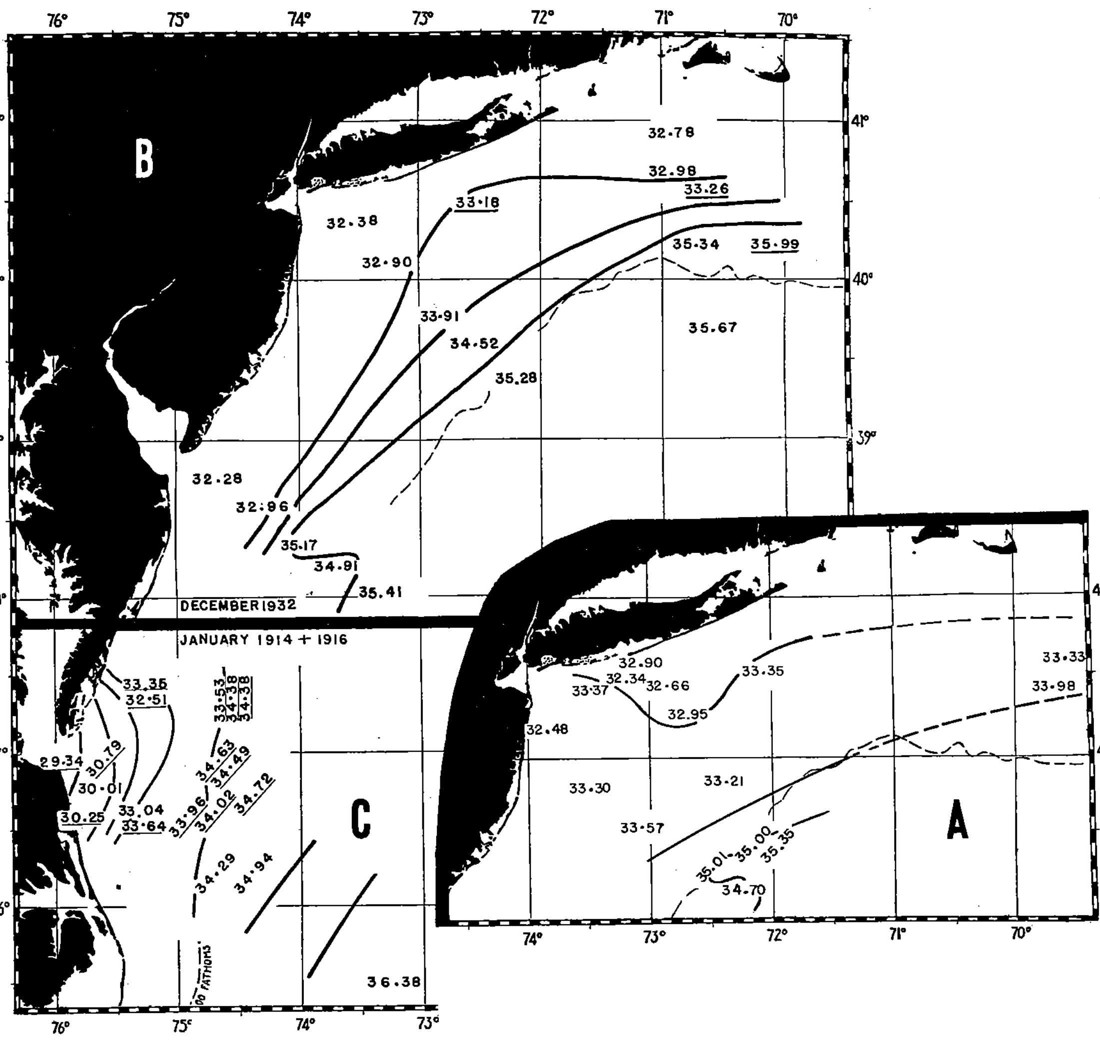


FIG. 47.—Salinity at the surface, late autumn and winter:—A, November 11–28, 1928, including data from Conseil Int. 1910–1932; B, December 19–22, 1932; C, January 20–27, 1914 and January 27–February 1, 1916 (the latter underlined).

between surface and bottom was only about 0.2 °/₀₀ per 20 meters at its steepest (stations New York II and Martha's Vineyard II); elsewhere less than 0.1 °/₀₀ and in most cases less than 0.05 °/₀₀ per 20 meters, offshore as well as inshore.

Autumnal equalization thus renders the water-column over most of the shelf as nearly homogeneous, vertically, by the end of December as it is at any time from then on, until the following spring. The only situation where the difference in salinity between surface and bottom may be considerable in midwinter is close in to the mouth of Chesapeake Bay on the one hand, where low surface salinities, in January of some years (p. 75, Fig. 47 C) produce an extremely steep gradient (mean, 3.00 ‰–4.00 ‰ per

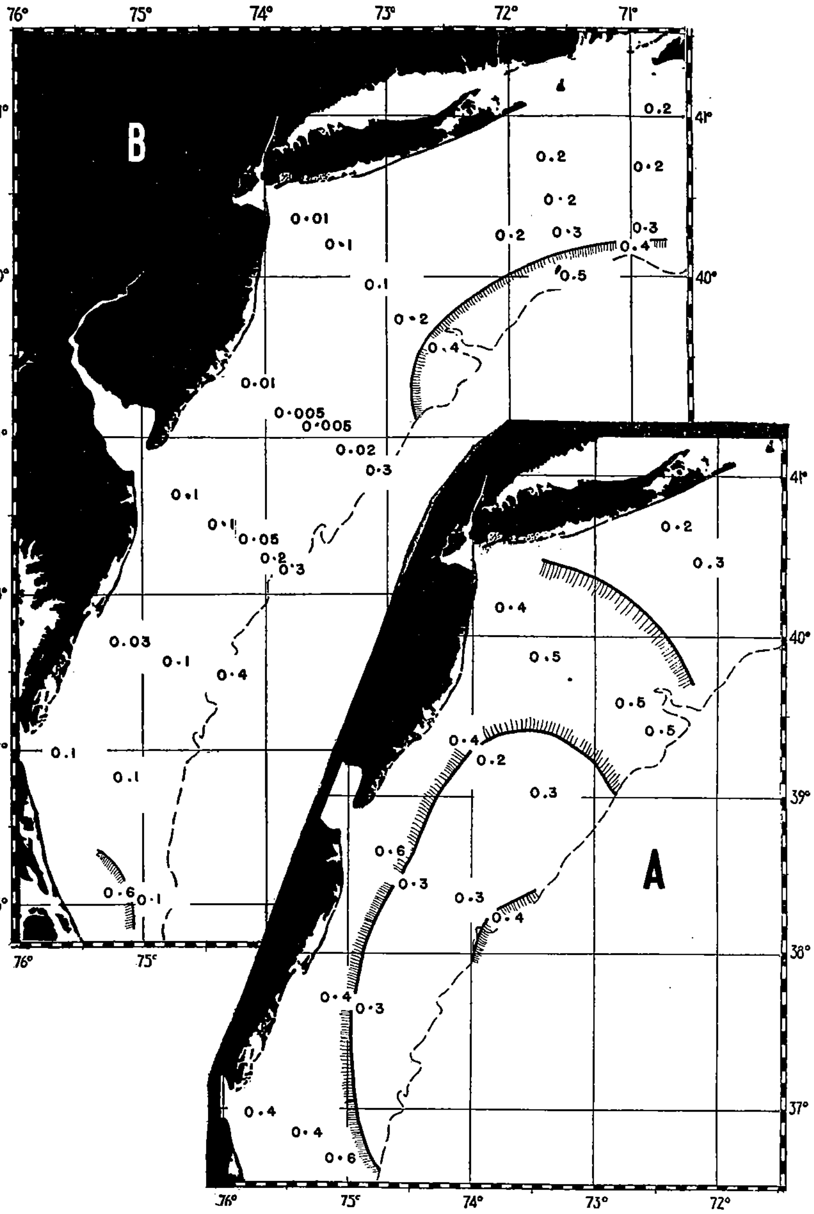


FIG. 48.—Mean vertical gradient of salinity (‰), per 20 meters of depth between surface and bottom:—A, September 3–10, 1932; B, October 19–28, 1931.

20 meters), and along the outermost zone on the other, where expansion of shelf water above slope water (or *vice versa*), may have a similar, though less pronounced, effect.[49]

In the case of temperature, vertical equalization, following the loss of heat, proceeds

[49] Mean gradients of 0.2 ‰–0.4 ‰ per 20 meters between surface and bottom.

from the surface downward. But in the case of salinity, the chief components of the controlling factors—mass movements of water of low salinity out from the land, and of high salinity in toward the coast—are nearer horizontal than vertical.[50] Furthermore, the density, at the temperature *in situ*, is usually lower for water from inshore than from offshore, and contributions are being received from both these sources, the year round. It follows that while the first step in the autumnal equalization of temperature is that the homogeneous surface stratum becomes thicker, salinity averages lower at the surface than deeper down—at least out to the 100-200 meter line—whether the total difference between surface and bottom be great as in summer, smaller, as in autumn, or smallest as in winter (Fig. 49.)[51] And comparatively homogeneous layers, contrasting with over- or underlying layers of discontinuity can be recognized until the time arrives (October–November, in different years) when the vertical gradient for the whole column, surface to bottom, has been reduced to the yearly minimum, as already described (p. 76).

The chief alteration, in distributional pattern, as illustrated in profile, that results from this progressive vertical equalization, is that a decrease takes place in the number of included isolines, and that the latter tend to rise more and more steeply from bottom toward sea-surface, across the shelf, as autumn advances.

If the normal seasonal sequence to conditions as existing in September 1932 (Fig. 50), be represented by the profiles for October, 1931 (Figs. 51, 52), a considerable alteration of this sort is already to be expected by mid-autumn. In the year in question, this change had proceeded most rapidly in the more southerly sector (Atlantic City and Chesapeake Bay profiles, Fig. 52). And the undulations in the individual isohalines show that the mixing processes responsible for it had involved complex laminary drifts inshore and offshore, at different levels. In some cases these had resulted in vertical reversals, with slightly lower values underlying slightly higher (Fig. 51 C, D), positive vertical stability being nevertheless maintained by temperature. And the fact that a similar phenomenon also appeared at the offshore end of the Chesapeake Bay profile for November 17, 1916 (Bigelow, 1922, Sta. 10414–10416), is cumulative evidence that such developments are characteristic of the time of year in this sector.

In the year 1931 (but whether annually or not is an open question) autumnal alteration seems to have proceeded less rapidly in the northerly part of the area, for definite stratification with isohalines close to horizontal (reminiscent of the summer state) not only persisted inshore there, until the last week of that October, but had spread right out across the outer edge of the shelf since July (Fig. 51 A), apparently as a result of some recent encroachment of slope water, shoreward over the sea floor.

The net result of these events is that, by December (Fig. 53), salinities, over the shelf, have once more returned to the winter state, so far as vertical distribution is concerned. But the early stages in autumnal progression cause very little alteration in the general pattern of distribution transverse to the shelf, as appears from the general correspondence between profiles for September (Fig. 50) and for July (Figs. 32, 42–44). The convergence-belt between shelf and slope waters seems, in particular, to have suffered no loosening by September of the only year (1932) when a survey was made in that month, for it still showed a horizontal transition of 1.5 ‰–2.00 ‰ in a distance of only 6–7 miles, in extreme cases (Fig. 50 B). These September profiles, in fact, show a more uniform and widespread interdigitation between these two types of water all

[50] The interaction between water and air, through evaporation and rainfall, is in rough equilibrium the year round.
[51] For examples of vertical reversals, see below, also pp. 10, 40, 50.

along from the offing of Chesapeake Bay to the offing of New York, than has been encountered on any other cruise, with (in each profile) higher salinities indenting shoreward at about the 20 meter level, and lower salinities spreading seaward at a slightly greater depth.

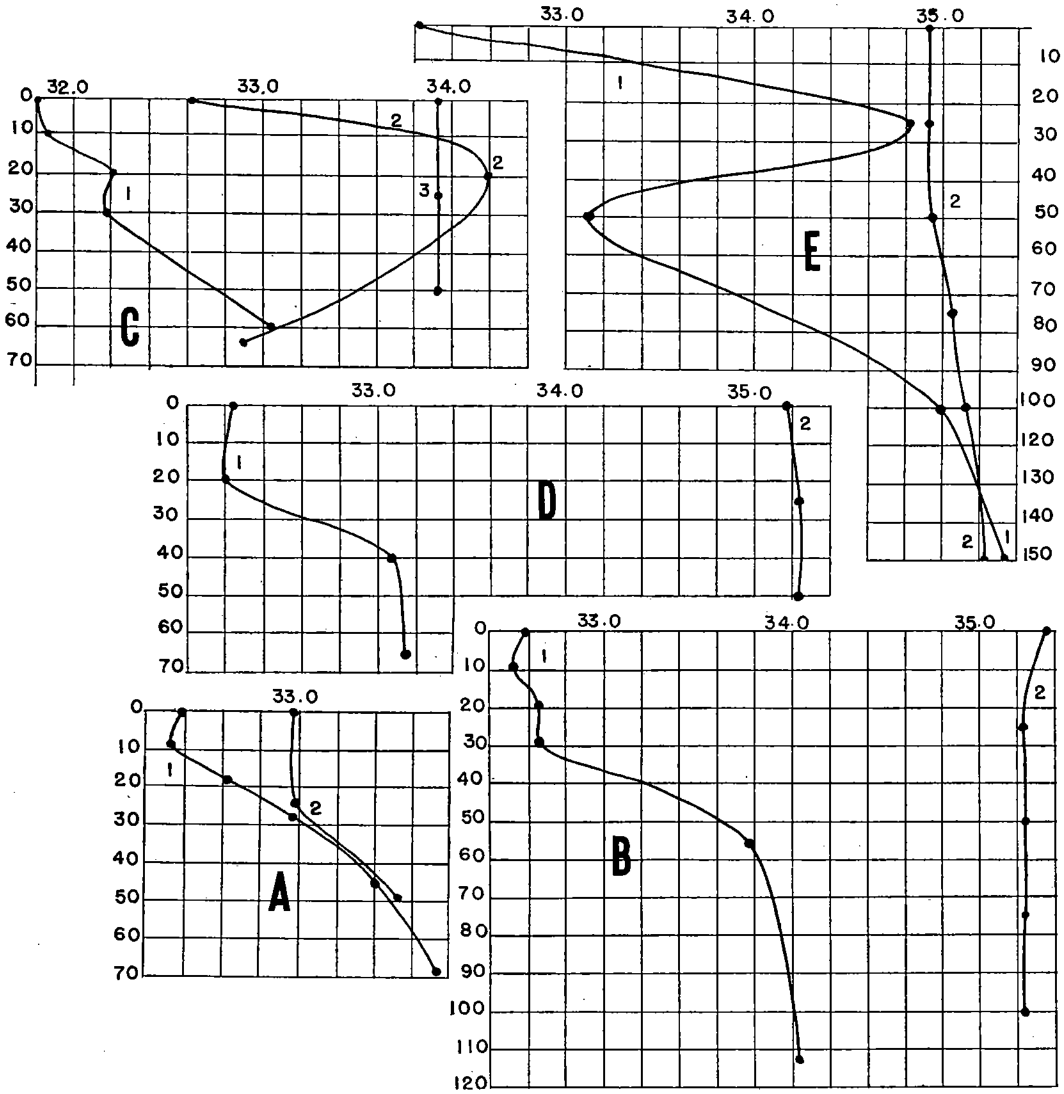


FIG. 49.—Vertical distribution of salinity, at representative stations, to show autumnal succession in 1932:—A, off Martha's Vineyard; (1) sta. III, July 19; (2) sta. II, December 21. B, off Martha's Vineyard; (1) sta. IV, July 19; (2) sta. III, December 21. C, Station New York III; (1) July 18; (2) Sept. 7. (3) December 20. D, Sta. Cape May III; (1) September 5; (2) December 19. E, Sta. Cape May IV; (1) September 5; (2) December 19.

In the eastern part of the area, represented by the New York profile (cf. Fig. 50 A with Fig. 44 C) this interdigitation had been produced since July, by a shelf-like intrusion, in over the outer part of the shelf, in the mid-depths, of water more saline than 34.5 ‰ from offshore. But the data do not tell how recent a development this may have been,

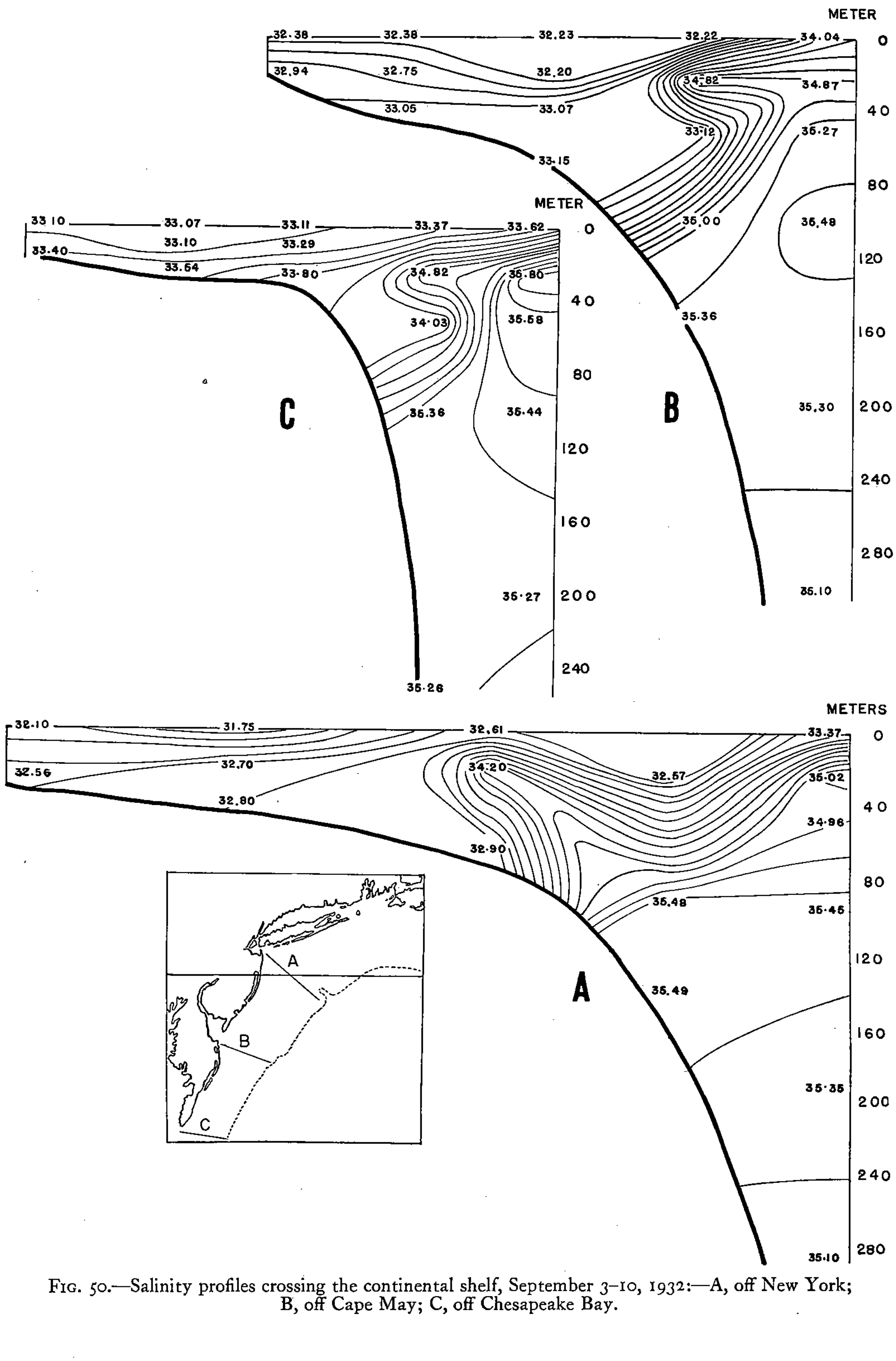


FIG. 50.—Salinity profiles crossing the continental shelf, September 3–10, 1932:—A, off New York; B, off Cape May; C, off Chesapeake Bay.

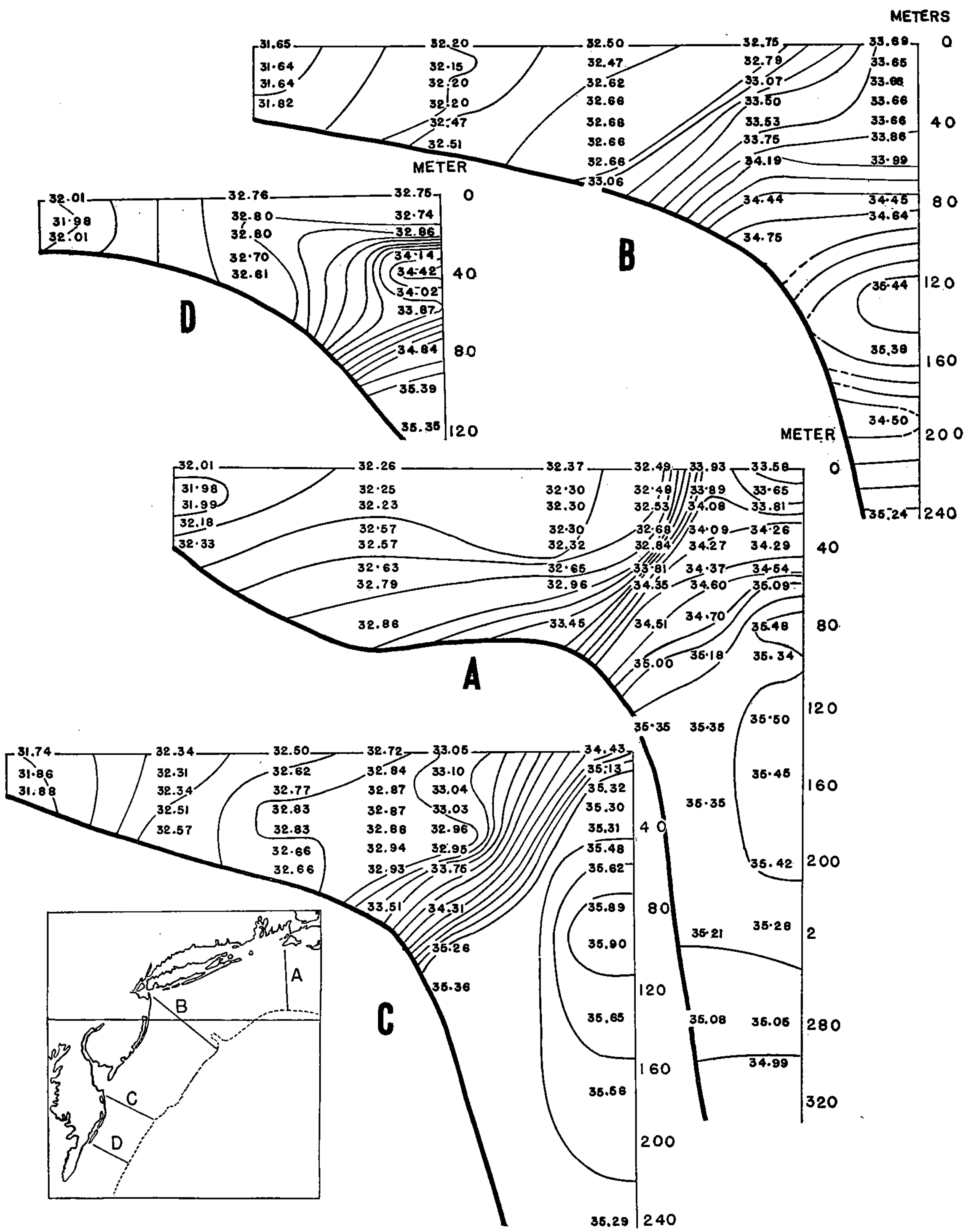

FIG. 51.—Salinity profiles crossing the continental shelf, October 21–24, 1931:—A, off Martha's Vineyard; B, off New York; C, off Cape May; D, off Winterquarter.

to the southward,[52] nor (lacking September data for any other year), whether such regularity of interdigitation is any more characteristic of early autumn than of any other time of year. However this may be, it is sufficiently established that developments of this sort may be very short lived. Consequently the fact that such interdigitation may be but irregularly represented on October profiles in a given year (e.g., 1931), does not necessarily indicate a normal tendency for them to weaken in mid-autumn. On the contrary, the convergence in question may be as abrupt, and as definite on some October

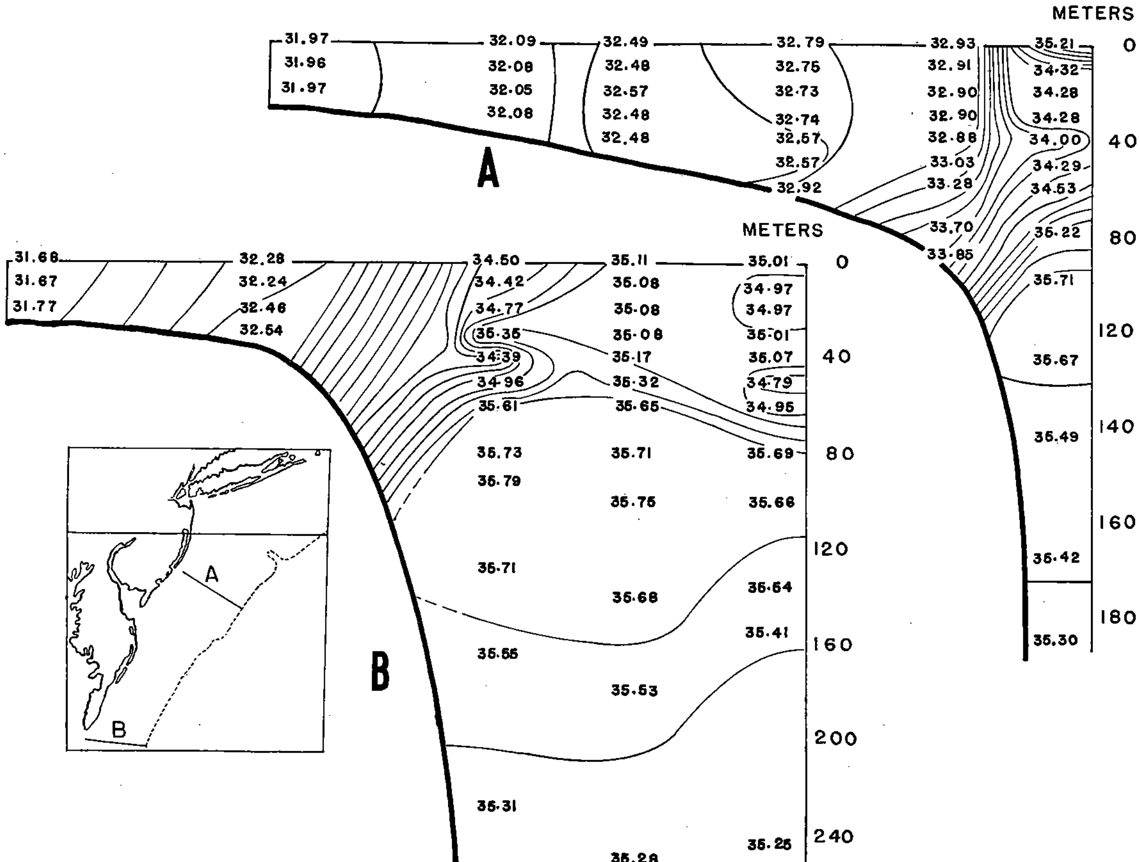


FIG. 52.—Salinity profiles crossing the continental shelf, October 22–25, 1931:—A, off Atlantic City; B, off Chesapeake Bay.

profiles as it ever is earlier in the season. In fact, the transitions shown near the edge of the shelf, on the Martha's Vineyard, Atlantic City and Winterquarter profiles for October, 1931 (Figs. 51 A, D, 52 A), are among the most abrupt, in both directions, yet recorded for our region. The contrast between the Martha's Vineyard profile and the corresponding New York profile (Fig. 51 B), on which the corresponding horizontal transition-belt ($33\ ^{\circ}/_{\circ\circ}$–$34\ ^{\circ}/_{\circ\circ}$) occupied a distance 4–5 times as great, shows how wide a difference may occur in this respect within a short distance, in autumn, as in spring and summer (p. 69).

[52] The July survey of 1932 covered only the northern and eastern part of the area.

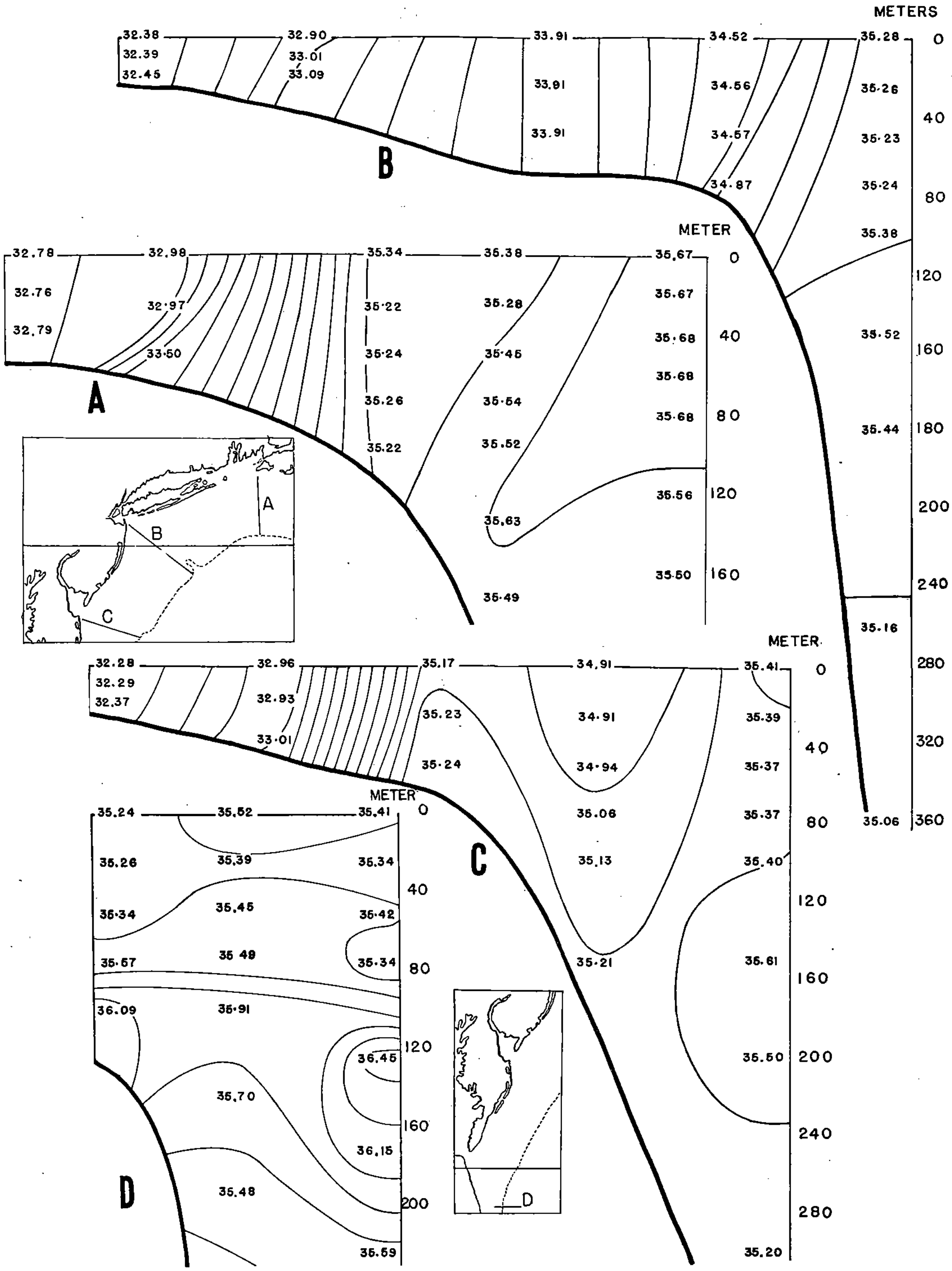


FIG. 53.—Salinity profiles crossing the continental shelf, December 19–21, 1932:—A, off Martha's Vineyard; B, off New York; C, off Cape May; also D, off Bodie Island, Nov. 30–Dec. 1, 1932.

In the year 1932—which we must perforce take as representative of the progression through autumn to early winter—further intrusion of slope water, below the surface took place in over the outer edge of the shelf sometime between September and Decem-

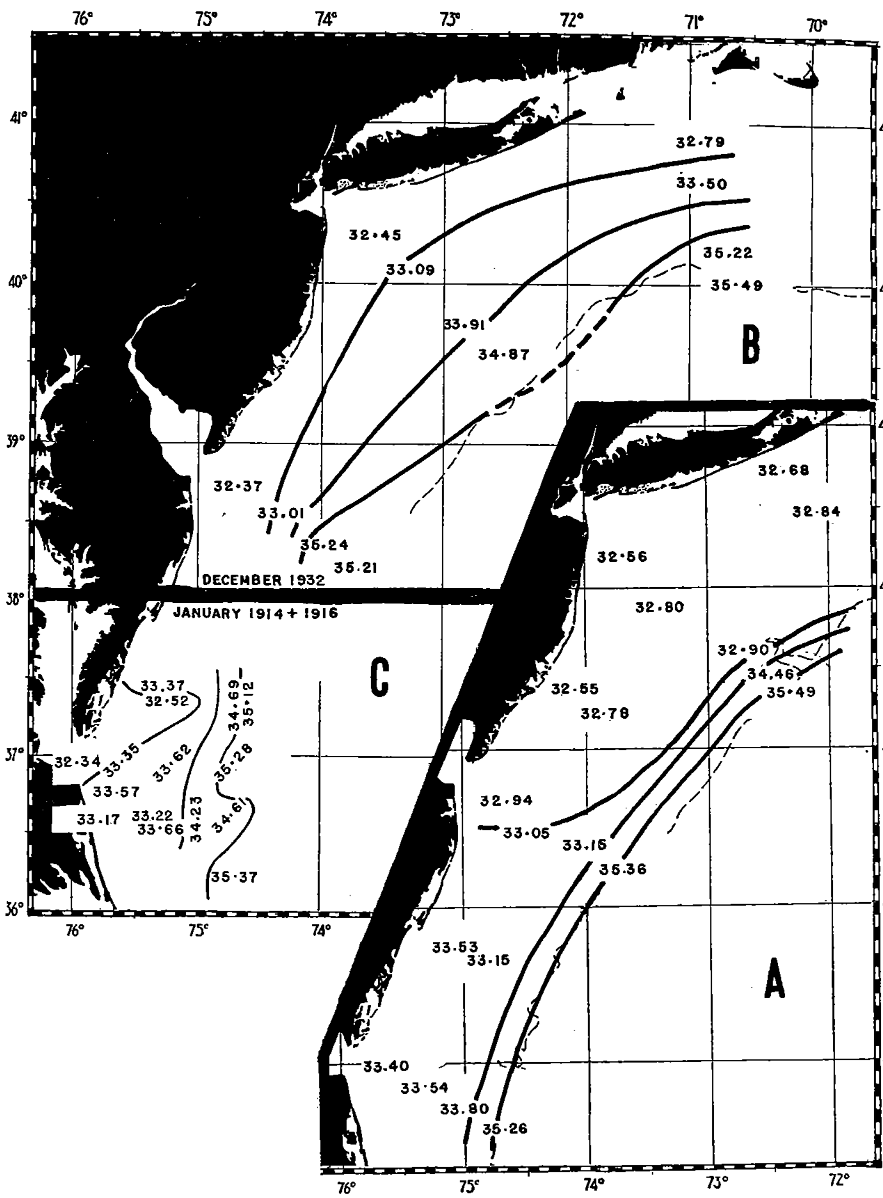


FIG. 54.—Salinity close to the bottom, out to the 200 meter contour only:—A, September 3–10, 1932; B, December 19–22, 1932; C, January 20–27, 1914 and January 27–February 1, 1916.

ber, illustrated by the notable shift, toward the coast, of the transition-belt between values lower than 33 °/₀₀ and higher than 34 °/₀₀ shown in profile (cf. Fig. 50 with Fig. 53), as well as by the corresponding rise in salinity on bottom (p. 86, Fig. 54). And though the seasonal schedule no doubt varies within wide limits from year to year, it is probable that something of this sort happens yearly, at about this same season, to account for the fact that subsurface salinities over the shelf rule considerably higher in winter than in summer or early autumn. But as pointed out below, late winter seems a period of comparative quiescence for bottom salinities (p. 86), in this respect.

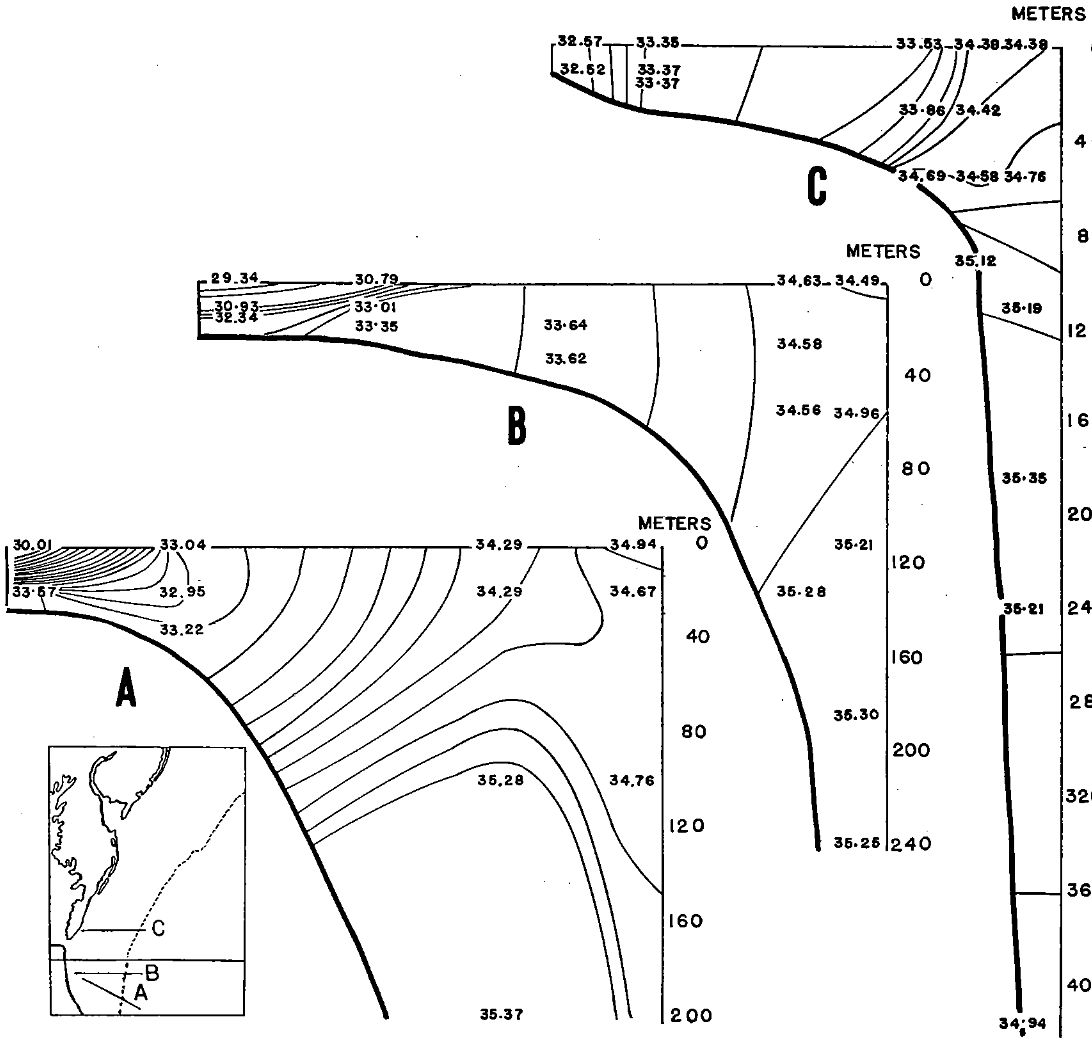


FIG. 55.—Salinity profiles crossing the continental shelf:—A, off Chesapeake Bay, January 20–27, 1914; B, off Chesapeake Bay, January 27, 1916; C, 17 miles north of Chesapeake Bay, January 28, 1916. *On account of crowding, the isohalines on profile B are for each 0.5 °/₀₀.*

A definite loosening of convergence between shelf and slope waters seems next to characterize the winter, for this transition was much less abrupt on the December profiles for 1932 (Fig. 53) than on those for September of that same year (Fig. 50), or for October of 1931 (Figs. 51, 52). And none of the profiles for early or for midwinter have shown any definite convergence, nearer the coast, between salinities of lowest and of medium values, except off Chesapeake Bay and a few miles to the southward (Fig. 55), where the steep vertical gradient already described for January of 1914 and of 1916 (p. 75) was also associated with horizontal transition much more abrupt than in October (Fig. 52 B), or in November (Bigelow, 1922, sta. 10416, 17) of the two autumns of record (1931, 1916). And the fact that the gradation across the shelf, in January 1916, was much more uniform only 17 miles north of the mouth of the bay (Fig. 55 C) shows how little effect the discharge from the latter exerts on salinities in that direction.

*Bottom.* Alterations that take place in salinity at the bottom, from summer through autumn, depend on the interaction between the freshening effect of progressive intermixture with less saline water from above, and on the contrary effects of indrafts of water of higher salinity from offshore. Should an autumn fall when the latter entirely failed, the salinity of the bottom strata on the shelf might be expected to decrease down to the greatest depth to which vertical mixing considerably diminishes pre-existing stratification, but no great alteration in bottom salinity would be expected at levels deeper than this. It may be that events never follow so simple a course as this in autumn, for our data all point to enough admixture of offshore water, either to prevent any appreciable decrease in bottom salinity through the autumn, or to cause some increase.

The early autumn of 1931 represents the first of these two alternate states, as appears from the comparative constancy in bottom values at corresponding depth-contours, between July and October, shown by the following table.

| | 40 M. | 50 M. | 75 M. | 100 M. | 150 M. |
|---|---|---|---|---|---|
| Martha's Vineyard Profile | | | | | |
| July | 32.0 | 32.4 | 32.4 | 34.3 | 35.20 |
| October | 32.3 | 32.4 | 32.8 | 34.2 | 35.35 |
| Montauk Profile | | | | | |
| July | 32.2 | 32.5 | 32.7 | >34.2 | — |
| October | ±32.3 | ±32.8 | 33.3 | 34.6 | — |
| New York Profile | | | | | |
| July | 32.4 | 32.8 | 33.0 | 34.6 | 35.4 |
| October | 32.0 | 32.4 | 33.1 | 34.6 | 35.3 |

The course of events in a year when the autumnal increment of offshore water is relatively greater, is illustrated by 1932, when the area occupied by bottom water more saline than 33.00 ‰–33.5 ‰ greatly expanded between September (Fig. 54 A) and December (Fig. 54 B); especially in the northeastern sector.

Available data[53] do not show whether a similar event is normally characteristic of early winter; the fact that 34 ‰ water had moved in to about the 60–70 meter contour off New York by November 10–15 of 1928 suggests that such may be the case. But since the inner boundary of bottom water of 34 ‰, for December 1932, occupied a position intermediate between that for February of 1929 and of 1930 (cf. Fig. 54 B with Fig. 9), it seems that the later winter is a season of comparative quiescence, so far as farther encroachments by slope water over the bottom are concerned.

If the late autumns and winters of 1914, 1916 and 1932 can be taken as representative, bottom salinities to be expected on the shelf for midwinter are about as shown in Figure 54, with maximum values of about 35.5 ‰ on the upper part of the continental slope, between the offings of Chesapeake Bay and of Martha's Vineyard. Unfortunately no profiles have yet been run near Cape Hatteras at that season, leaving it an open question whether oceanic water of 36 ‰ touches the slope near the cape between early autumn and January, as it does both at the end of winter, and in summer. Presumably such is,

[53] No December data for other years.

however, the case, judging from the fact that on November 30, 1932, water of 36 °/₀₀ was encountered at the 100 meter level, just inshore of the 200 meter contour off Bodie Island (Fig. 53 D).

## SUMMARY

### GENERAL

The distribution of salinity over the continental shelf, Cape Cod to Chesapeake Bay, is coastal in character, with values increasing from 32 °/₀₀, or less, next the land, and 32–33.5 °/₀₀ over the mid-zone of the shelf, to 34–35 °/₀₀ near the continental edge, where complex interdigitations may occur along the zone of mixture between inshore and offshore waters. Water slightly more saline than 35 °/₀₀ is normally in contact with the bottom on the upper part of the continental slope, with slightly lower values deeper down the slope.

There is little difference in salinity (and no abrupt transitions) lengthwise of the shelf, from the Gulf of Maine in the northeast nearly to Cape Hatteras, regardless of depth or season. Just south of Cape Hatteras, however, a wedge of pure oceanic water (>35.5 °/₀₀) presses in across the shelf (here only 27 miles wide) causing an extremely abrupt transition, southward, to much higher values, and entirely separating the shelf and slope water bands to the north from the low coastal salinities farther south. Available data suggest that this situation exists throughout the year.

The chief factors tending to alter the basic salinity pattern over the shelf are:—(1) freshening by river water (Fig. 12) entering close to the surface inshore, and (2) salting by indrafts of slope water, over the bottom from offshore. The latter similarly affects (i.e., increases) temperature. But the former does not appreciably affect temperature, while the chief warming and cooling factors (solar and back radiation) affect salinity only indirectly.

Salinity is at its maximum at the end of the winter. The voluminous discharge of land water, in spring, reduces it to its minimum by early summer. Through the autumn, when indrafts from offshore more than counterbalance the inflow of river water, and when vertical mixing becomes more active as vertical stability is reduced by surface chilling, salinity again increases, and its distribution returns to the winter state.

### WINTER MAXIMUM

Salinities on the shelf are highest in late February or early March, surface values between the offings of Martha's Vineyard and of Chesapeake Bay then averaging about 34.1 °/₀₀ along the continental edge (200 meter contour); about 33.5 °/₀₀ along the mid-belt of the shelf, and about 32–33 °/₀₀ at the inshore stations, with values <32 °/₀₀ confined to the mouths of Delaware and Chesapeake Bays, and alongshore from the latter. The lowest value recorded, for the open sea, at this season, was about 30 °/₀₀.

The vertical range of salinity on the shelf averages smallest in winter, steep gradients at that season being confined to inshore localities where lowest surface values show recent increments of river water. Elsewhere, out to the 80–90 meter contour, the rate of vertical change in salinity, in February–March, has averaged less than 0.1 °/₀₀ per 20 meters of depth, usually with salinity lowest at the surface, but occasionally with small vertical reversals. Along the edge of the continent (100–200 meter zone), increase in salinity, with depth, is usually (but not always) more rapid in the deeper strata. Outside the 200 meter contour line, vertical distribution may or may not be complicated by interdigitation between shelf and slope waters (usually with maximum values at 150–175 meters), and a definite convergence often develops along short sectors. Below 300 meters, there is little vertical alteration, salinity being about 34.9 ‰ down to 900–1000 meters, and in some profiles the outermost station has lain in a belt of water homogeneous downward, from 100 meters or so.

Mean bottom values, February–March, are about 32.5 ‰ along the 20 meter line; 33.4 ‰ at 30–45 meters; 33.5 ‰ at 45–60 meters. At 60–100 meters mean values increase from about 32.8–33.3 off Martha's Vineyard, to 34.2–34.6 off Chesapeake Bay. Between 110–240 meters and 300–500 meters, water of 35–35.5 ‰ touches bottom along the slope usually (but not always) as a continuous band; in some winters as far eastward as longitude about 68°, but perhaps never farther east.

## VERNAL PROGRESSION

On the average about 50 per cent of the total annual discharge of river water is concentrated in March, April, and May (Fig. 12). The resultant freshing, while extremely irregular, is considerable over the whole shelf, as far north and east as longitude 71° 30′, but hardly affects the short sector thence eastward, past Martha's Vineyard, to Nantucket Shoals. Freshing is most pronounced close in to the sites of discharge; approximate minimum values to be expected 8–10 miles out from land, during spring, are:—Martha's Vineyard, 31.9–32 ‰; Montauk, 30.8 ‰; New York, 27 ‰; Atlantic City, 30.3 ‰; Cape May, 30.5 ‰; coast of Virginia, 31.3 ‰; Chesapeake Bay, about 27 ‰; Bodie Island, 30 ‰. Minimal values, inshore, may develop in April, May, June, or even in summer; east of New York, the mean for June is about the same as for May (Fig. 11). Values below 31 ‰ are confined to small pools, but by some time in May, a band less saline than 32 ‰ develops along the coast as far as longitude 71° 30′, either continuous, or more or less interrupted. The isohaline for 32 ‰ indicates that the outflow from Long Island Sound spreads offshore and westward; that from New York harbor offshore and southward. The discharge from Delaware Bay seems chiefly to be incorporated nearby; that from Chesapeake Bay may or may not form a temporary fan.

Available data indicate that surface water $<32$ ‰ develops to greatest breadth in the offing of New York, where it may spread offshore for 90–100 miles; whereas off Chesapeake Bay, it is never more than about 50 miles broad. To the southward of Delaware Bay it reaches its greatest expansion before June, contracting thereafter, either to isolated pools or disappearing altogether. To the northward, it may reach its greatest breadth in May, with no great change in June; or it may continue to expand during the latter month, with surface water $>33$ ‰ withdrawing to the outer edge of the shelf, or even beyond the latter.

In some years when indrafts of slope water are small, or in sectors but little affected thereby, the effects of vernal freshening (decreasing with depth) are appreciable down to 70–80 meters: in 1929 the bottom out to this depth was 0.3–1.00 ‰ less saline in April than in February. But strong pulses of slope water may cause alteration of the reverse order in the deeper strata along the outer belt of the shelf. In spring such indrafts occur chiefly close to bottom: their volume, date, and extent of area affected, vary widely from year to year. In 1930, widespread encroachment of water $>34$ ‰ took place between February and April, followed, by May, by withdrawal of the isohaline for 34.5 ‰ to about the position it had occupied in February. In years of this type, the effects of vernal freshening may thus be entirely counteracted, on bottom, right in to the 20 meter line. In the other years of record (1929, 1931 and 1932) indrafts of slope water during the spring were so much less extensive that bottom salinities decreased from February to May and June.

Freshening at the surface, and indrafts of slope water below, combine to increase the vertical gradient of salinity over the shelf as a whole, though this alteration is much less regular, both seasonally and regionally, for salinity than for temperature. Steepest gradients develop in the upper 20 meters off New York, off Delaware Bay, and especially off Chesapeake Bay where a mean vertical gradient of >8 ‰ per 20 meters has been recorded on three occasions. But in such situations the gradient may alternately increase, decrease and increase again within short periods. Comparatively steep gradients may also develop temporarily within short sectors along the continental edge, depending on the interaction there between shelf water (<33 ‰) and slope water (>35 ‰). Elsewhere over the shelf, and especially to the eastward of New York, the vertical gradient usually continues much smaller. The increasing vertical gradient may be variously distributed between surface and bottom, regional contrasts being widest in this respect in May, and tending somewhat to smooth out in June. Successive isohalines tend to assume positions more nearly horizontal across the shelf with the advance of spring; a convergence zone tends to develop between coast water (recently freshened) and shelf water; while a steeper convergence between shelf and slope waters appears over the outer edge of the shelf on many of the spring and early summer profiles.

On the other hand, interdigitation of higher and lower salinities, along the slope seems no more active in spring than in winter, for only 4 April-May profiles, out of 11, show it; it also appears on some June profiles but not on all.

## MIDSUMMER

In exceptional years (e.g., 1916, 1927), the effects of vernal freshening may not culminate before late summer. In normal years, however, the band <32 ‰ shows little expansion or contraction from June through August; the trend of mean values to the east of New York is almost stationary during this period, and inshore values may be as low as in June (Fig. 11). In individual years the inshore belt <32 ‰ may either be continuous, in July, extending out to the edge of the shelf off New York, or it may already be broken into isolated pools. Similarly, the isohaline for 33 ‰ may still lie outside the 100–200 meter zone with 34 ‰ nearby, or it may already be well inshore of the continental edge. To the northward of latitude 39°, in July–August, surface water of 35 ‰ is 10–70 miles out from the continental edge, but it is close to the latter, or even inshore of it, off Chesapeake Bay. And water of 36 ‰, which to the northward is well offshore, is close in to the shelf off Cape Hatteras.

In July–August, as in spring, very steep vertical gradients may occur off New York, and especially off the mouth of Chesapeake Bay, where a gradient of 12.25 ‰ per 20 meters was recorded on August 21, 1916, the opposite extreme being illustrated by Nantucket Shoals, where turbulence keeps the water close to homogeneous, in salinity, throughout the summer. And while no widespread alteration takes place in distributional pattern, and no general strengthening of the belts of convergence between the different waters, it is in July–August that the vertical gradient averages steepest over the mid- and outer belts of the shelf. Station to station transitions in vertical distribution are widest at that season, small vertical reversals are then most frequent inshore, and the profiles show interdigitation along the slope more frequently in late summer than in May and

June. On the other hand, the extent of bottom, along the upper slope bathed by water >35 °/₀₀ shows no general alteration from spring through summer, yearly differences in this respect being much greater than any regularly seasonal expansions or contractions.

The normal range of salinity, on bottom in the region as a whole in July–August is approximately as follows:—40 meters, 32.6–33.1 °/₀₀; 50 meters, 32.8–33.6 °/₀₀; 75 meters, 33.5–33.9 °/₀₀; 100 meters, 33.6–34.6 °/₀₀; values on the outer belt of the shelf average 0.3–0.4 °/₀₀ higher in the offing of Chesapeake Bay than to the northward. The lower boundary of bottom water of 35 °/₀₀ usually lies between 250–500 meters; occasionally as deep as 800 meters. Still deeper down the slope, bottom values are close to 34.9 °/₀₀. The annual variation in the bottom salinity in summer, out to the 100 meter line, is 0.5–1.5 °/₀₀ on the upper part of the continental slope. But bottom values below about 150 meters show a maximum yearly range of only about 0.5 °/₀₀ (35.0–35.5).

The maximum recorded value along the slope as defined by the 200–1200 meter contour, at any intermediate depth between the offings of Chesapeake Bay and Martha's Vineyard, is 35.4–35.7 °/₀₀. Farther south near Cape Hatteras, water >36 °/₀₀ is over the slope in summer as it is also in winter. It may also come within 25 miles of the continental edge near longitude 69°, at the 40–100 meter level, but it is much farther out along the intervening sector, its distance from the continental edge off New York usually being more than 150 miles.

## AUTUMNAL PROGRESSION

The slight increase in the rate of discharge from the rivers, from summer through autumn (Fig. 12), is not sufficient to counteract the effect of surface cooling in reducing the vertical stability of the water column, and permitting increasingly active mixing. The vertical range of salinity between surface and bottom thus tends to decrease during the autumn, the surface salinity to increase, but the rapidity of these changes varies from year to year. In 1934, for example, surface salinities had risen 0.3–0.7 °/₀₀ above the summer minimum by September, whereas in 1931 only a slight increase had taken place by mid-October. Mean values east of New York, average about 0.7 °/₀₀ higher for September than for July; about 0.1 °/₀₀ higher in October than in September. Even in years (e.g., 1916) when summer salinities are abnormally low, and the seasonal schedule correspondingly delayed, surface values have increased considerably by November. And while, in more normal years, the eastern sector shows little mean alteration offshore through October and November, all readings close in to New York for November have been >32.0 °/₀₀. The general trend from November through December (as indicated by mean values to the east of New York) is either close to stationary, or values >35 °/₀₀ may press in over the extreme edge of the slope (e.g., 1932). Further increase of 0.3–0.4 °/₀₀ in January brings the surface salinity again to its annual winter maximum, except that very low values (29–30 °/₀₀) have been recorded in the immediate offing of Chesapeake Bay in January of two years. This general increase in surface salinity is accompanied by dissipation of any pools of low salinity off New York, and off the bays to the southward and tends to equalize the regional contrast, thus bringing the horizontal distribution back to the more simple state characteristic of late winter.

The fact that subsurface salinities also increase through autumn, to reach their yearly maximum in winter is conclusive evidence that indrafts from offshore, at that season, are sufficient to counteract not only the coincident inflow of river water, but also the accumulated surplus of the latter. Clear evidence of such indrafts, between September and December is afforded by the data for 1932. But it is not likely that an autumn ever falls when such indrafts are rapid enough to prevent some progressive vertical equalization of salinity, and some slackening of the offshore convergence between shelf and slope waters. Interdigitation along the continental edge between shelf and slope waters may, indeed, strengthen from July to September (e.g., in 1932); convergence between these two waters has been as abrupt on some of the October profiles as at any time of year; and, comparatively homogeneous strata above strata of discontinuity may also persist through late autumn. But in most years, considerable decrease in the vertical gradient has already taken place by October. And by December, it averages less than 0.1 °/₀₀ per 20 meters, over the shelf as a whole, so to continue during the next two months. The only notable exceptions to this rule are in the immediate vicinity of the mouth of Chesapeake Bay, where recent discharges of land water may cause extremely steep vertical gradients near land, in January of some years.

As vertical equalization progresses, the isohalines included on any given profile not only decrease in number, but tend to rise more steeply from the bottom toward the surface. The net result is that by December, the vertical pattern of salinity has returned to the winter state, described above.

### REGIONAL DISTRIBUTION BY SEASONS

The regional distribution is shown in the following figures:—

Surface: February–March, Figs. 1 B, C, 2 A; May, Figs. 13, 16, 17 (maximum, minimum, and mean); June, Fig. 28; July, Figs. 36, 37; September–November, Fig. 46; November–January, Fig. 47; seasonal succession east of New York, Fig. 11.

Bottom: February–March, Figs. 2 A, 9; April–May, Figs. 26, 27; June, Fig. 34; July–August, Fig. 45; September–January, Fig. 54.

Yearly limits of variation, July, at representative stations, Figs. 39, 40.

Mean July profile off New York, Fig. 44 D.

Distribution of discharge of river water, by seasons, Fig. 12.

## TEMPERATURES AND SALINITIES TAKEN ON MR. ISELIN'S CRUISES, ON THE YACHTS "CHANCE" AND "ATLANTIS I", AT STATIONS ON THE CONTINENTAL SHELF AND OFFSHORE WITHIN 120 MILES OF THE 200 METER CONTOUR LINE, WEST OF LONGITUDE 69°30′.

The data for each station are given in the following order: Serial number; Profile (Fig. 1); Station number on the profile; Latitude (N); Longitude (W); month (Roman numerals); day of month; bottom depth in meters (only at a few stations); depth in meters for each observation, followed by temperature (°C) and salinity (°/₀₀). For further explanation, see Bigelow, 1933, p. 104. Depths of observations were measured by the length and angle of wire outboard, and are, therefore, subject to an indeterminate error at the deeper levels.

### Cruise of June 21 to July 28, 1927, "Chance" Series

101 Cape Hatteras I, 35.27, 75.22; VI/21:—0, 19.4, 28.66;[1] 10, 18.8; 26.80;[1] 20, 18.2, 29.99.
102 Cape Hatteras II, 35.25, 75.17; VI/21:—0, 18.2, 30.48; 10, 17.6, 30.72; 25, 16.35, no sal.
103 Cape Hatteras III, 35.23, 75.10; VI/21:—0, 18.3, 31.82; 10, 17.8, 31.76; 25, no temp., 33.93.
104 Cape Hatteras IV, 35.22, 75.04; VI/21:—0, 24.9, 35.62; 25, no temp., 36.13; 50, 23.3, 36.29; 100, 18.4, 36.18.
105 Cape Hatteras V, 35.21, 74.57; VI/21:—0, 25.1, 36.24; 50, 24.05, 36.27; 100, 19.8, 36.33; 200, 13.0, 35.57; 300, 8.85, 35.21; 400, 8.4, 35.19; 500, 7.1, 35.07; 600, 6.0, 35.00; 700, 5.15, 34.96.
106 Cape Hatteras VI, 35.50, 74.30; VI/22:—0, 28.00, 35.97; 100, 25.5, 36.36; 200, 17.7, 36.08; 300, 14.65, 35.77; 500, 11.85, 35.30; 600, 10.3, 35.17; 700, 8.7, 35.10; 800, 7.45, 35.05; 1000, no temp., 34.99.
120 Cape May IX, 36.49, 72.07; VII/20:—0, 26.4, 34.36; 50, 26.0, 36.27; 100, 21.35, 35.91; 200, 20.8, 36.45; 300, 11.6, 35.05; 400, 11.5, 35.39; 600, 9.25, 35.03; 800, 7.25, 35.16.
121 Cape May VIII, 36.54, 72.17; VII/20:—0, 23.8, 34.27; 25, 23.5, 34.04; 50, 17.75, 34.61; 100, 11.85, 35.05; 200, 11.95, 35.46; 300, 9.7, 35.16; 400, 7.65, 35.07; 500, 5.95, 34.88; 600, 5.55, 35.07; 700, 4.65, 35.10.
122 Cape May VII, 37.04, 72.32; VII/21:—0, 24.0, 33.64; 25, 24.9, 34.69; 50, 17.55, 35.39; 100, 13.85, 35.64; 200, 9.4, 35.17; 300, 7.95, 35.12; 400, 5.75, 35.01; 500, 4.65, 35.17; 600, 4.4, 35.05.
123 Cape May VI, 37.16, 72.53; VII/21:—0, 24.2, 34.33; 50, 16.2, 35.88; 100, 12.35, 35.43; 200, 8.8, 35.19; 300, 6.2, 34.97; 400, 5.25, 35.05; 500, 4.4, 34.97; 600, 4.3, 34.94; 800, 4.1, 34.97; 1000, 3.8, 34.97; 1200, 3.5, 35.03.
124 Cape May V, 37.30, 73.18; VII/21:—0, 22.3, 34.70; 25, 18.85, 34.92; 50, 14.05, 35.61; 100, 12.0, 35.53; 200, 9.3, 35.05; 300, 6.5, 35.01; 400, 4.85, 34.92; 500, 4.5, 34.97; 600, 4.3, 35.01; 800, 4.0, 34.88; 1000, 3.85, 34.96; 1200, 3.75, 34.97.
125 Cape May IV, 37.41, 73.34; VII/21:—0, 22.0, 34.60; 25, 17.95, 34.81; 50, 12.2, 34.97; 100, 12.0, 35.62; 200, 9.6, 35.35; 300, 7.25, 34.94; 400, 5.5, 35.03; 600, 4.5, 35.03; 800, 4.05, 35.05; 1000, 3.95, 35.01; 1200, 3.55, 34.85.
126 Cape May III, 38.01, 74.11; VII/22:—0, 21.4, 32.63; 25, 19.0, 32.61; 50, 6.65, 33.08; 75, 7.65, 33.71; 110, 11.05, 34.94.
127 Cape May II, 38.09, 74.27; VII/22:—0, 22.45, 31.83; 10, 22.0, 31.76; 30, 8.85, 32.66; 50, 7.45, 32.88.
128 Cape May I, 38.16, 74.42; VII/22:—0, 23.2, 31.27; 10, 20.25, 31.20; 30, 7.6, 32.36.
129 Atlantic City I, 39.26, 73.45; VII/24:—0, 21.7, 31.33; 10, 21.7, 31.26; 30, 7.35, 32.57.
130 Atlantic City II, 39.20, 73.28; VII/24:—0, 21.6, 31.46; 10, 21.3, 32.07; 25, 8.3, 32.61; 45, 5.8, 32.27.
131 Atlantic City III, 39.13, 73.09; VII/24:—0, 22.05, 31.46; 10, 21.6, 31.65; 30, 8.9, 32.88; 50, 4.95, 33.04.
132 Atlantic City IV, 39.05, 72.48; VII/24:—0, 23.3, 32.29; 25, 13.25, 33.19; 50, 4.75, 32.75; 75, 4.8, 32.97; 150, 10.55, 35.35; 250, 7.95, 35.01.
133 Atlantic City V, 38.58, 72.30; VII/24:—0, 21.3, 32.27; 50, 11.85, 33.95; 100, 11.35, 34.67; 200, 8.95, 35.10; 250, 7.6, 35.08; 300, 6.2, 35.03; 400, 4.8, 34.94; 500, 4.55, 34.81; 600, 4.15, 34.96; 800, 4.1, 35.03; 1000, 3.75, 34.99.
134 Atlantic City VI, 38.44, 71.51; VII/25:—0, 20.5, 32.45; 25, 18.75, 34.83; 50, 10.65, 34.69; 100, 11.45, 35.16; 200, 10.0, 35.28; 300, 7.3, 35.03; 400, 4.95, 34.76; 600, 4.2, 34.92; 800, 3.9, 34.94; 1000, 3.75, 35.01; 1200, 3.65, 34.96.
135 Atlantic City VII, 38.35, 71.32; VII/25:—0, 23.6, 34.74; 25, 18.35, 34.63; 50, 14.0, 34.94; 100, 13.1, 35.88; 200, 10.05, 35.34; 300, 7.8, 35.05; 400, 5.3, 34.79; 500, 4.8, 35.01; 600, 4.3, 34.97; 800, 3.8, 34.96; 1000, 4.0, 35.03; 1200, 3.5, 34.97.
136 Atlantic City VIII, 38.28, 71.08; VII/25:—0, 23.8, 34.76; 50, 13.25, 35.17; 100, 12.65, 35.59; 200, 9.8, 35.43; 300, 7.4, 35.12; 400, 5.25, 35.05; 500, 4.65, 34.90; 600, 4.15, 34.97; 800, 4.10, 34.96; 1000, 3.8, 35.03.
137 Atlantic City IX, 38.22, 70.48; VII/25:—0, 24.4, 35.35; 25, 22.05, 35.46; 50, 14.6, 34.90; 100, 12.45, 35.41; 200, 10.1, 35.28; 300, 7.3, 34.94; 400, 5.85, 35.10; 600, 4.6, 34.99; 800, 4.1, 35.01; 1000, 4.0, 35.01.
138 Atlantic City X, 38.09, 70.15; VII/26:—0, 34.4, 34.56; 25, 22.05, 34.97; 50, 14.6, 35.17; 100, 12.45, 35.57; 200, 10.1, 35.21; 300, 7.3, 34.88; 400, 5.85, 34.94; 600, 4.6, 34.90; 800, 4.1, 34.85; 1000, 4.0, 35.08; 1200, 3.6, 34.96.
139 Martha's Vineyard XI, 38.01, 69.45; VII/26:—0, 26.5, 35.05; 50, 26.0, 36.27; 200, 15.4, 35.44; 300, 10.35, 35.30; 400, 8.45, 35.10; 500, 7.6, 35.21; 600, 7.2, 35.10; 800, 5.8, 35.17; 1000, 4.8, 34.92.
140 Martha's Vineyard X, 38.19, 69.39; VII/26:—0, 24.5, 34.40; 25, 19.95, 35.01; 50, 13.7, 35.43; 200, 10.0, 35.35; 300, 7.35, 35.26; 400, 5.55, 35.07; 600, 4.35, 35.07; 800, 4.1, 35.14; 1000, 3.7, 35.14.
141 Martha's Vineyard IX, 38.39, 69.34; VII/27:—0, 23.3, 34.00; 25, 18.8, 35.32; 50, 12.25, 34.92; 100, 13.5, 33.80; 200, 12.95, 35.68; 300, 10.3, 35.35; 400, 7.7, 34.96; 800, 3.75, 34.99; 1200, 3.55, 35.10.
142 Martha's Vineyard VIII, 38.58, 69.42; VII/27:—0, 21.95, 33.48; 25, 15.65, 34.05; 50, 8.35, 33.93; 100, 11.35, 35.26; 200, 10.55, 35.41; 300, 8.1, 35.23; 400, 5.75, 35.01; 600, 4.3, 35.07; 800, 4.05, 35.07; 1000, 3.85, 35.03; 1200, 3.65, 34.97.
143 Martha's Vineyard VII, 39.21, 69.50; VII/27:—0, 24.95, 35.34; 25, 21.9, 35.41; 50, 15.9, 35.14; 100, 12.2, 35.19; 200, 11.5, 35.41; 300, 8.55, 35.32; 400, 6.25, 35.12; 600, 4.4, 35.01; 800, 4.05, 35.01; 1000, 3.85, 34.94.
144 Martha's Vineyard VI, 39.35, 69.55; VII/27:—0, 23.8, 34.65; 25, 20.5, 35.25; 50, 15.5, 35.35; 100, 12.0, 35.41; 200, 10.5, 35.35; 300, 7.95, 35.23; 400, 6.15, 35.10; 600, 4.4, 35.08; 800, 4.0, 35.10.
145 Martha's Vineyard V, 39.58, 70.08; VII/28:—0, 21.45, 33.35; 25, 20.15, 35.16; 50, 8.65, 33.73; 100, 11.45, 35.07; 200, 10.15, 35.25.
146 Martha's Vineyard IV, 40.17, 70.14; VII/28:—0, 21.2, 32.07; 25, 8.3, 32.61; 50, 5.95, 32.99; 75, 7.9, 33.84; 100, 9.45, 34.79.
147 Martha's Vineyard III, 40.32, 70.19; VII/28:—0, 20.15, 31.94; 10, 16.6, 32.01; 20, 8.4, 32.43; 45, 7.25, 32.72.
148 Martha's Vineyard II, 40.48, 70.21; VII/28:—0, 20.6, 31.60; 10, 18.35, 31.64; 20, 10.15, 32.50; 45, 9.3, 32.56.
149 Martha's Vineyard I, 41.04, 70.26; VII/28:—0, 19.0, 31.78; 15, 10.9, 32.38; 35, 9.0, 32.54.

### Cruise of June 26–29, 1928; "Iselin" Series

201 Atlantic City II, 39.39, 73.06; VI/26:—D67: 0, 17, 31.56; 25, 10.45, 32.79; 50, 6.65, 33.20.
202 Atlantic City III, 39.28, 72.53; VI/26:—D71: 0, 17.5, 32.39; 10, 16.3, 32.23; 30, 7.2, 32.97; 50, 7.0, 33.24; 60, 6.8, 33.35.

[1] These two readings were probably transposed.

203 Atlantic City IV, 39.22, 72.44; VI/26:—D109: 0, 17.0, 32.74; 25, 15.05, 34.54; 50, 11.5, 34.71; 100, 10.8, 34.92.
204 Atlantic City V, 39.14, 72.34; VI/26:—D142: 0, 18.3, 33.33; 25, 14.0, 34.43; 50, 12.35, 34.90; 100, 10.85, 35.03.
205 Atlantic City VI, 39.03, 72.19; VI/26:—0, 20.3, 35.01; 25, 18.05, 35.26; 50, 12.2, 34.71; 100, 12.25, 35.53; 200, 10.6, 35.34; 300, 8.15, 35.08; 400, 6.25, 35.05.
206 Atlantic City VII, 38.46, 71.56; VI/27:—0, 21.0, 34.92; 50, 14.95, 35.55; 100, 12.9, 35.46; 200, 11.05, 35.48; 300, 9.65, 35.21; 400, 7.65, 35.17; 600, 5.1, 35.13; 800, 4.2, 35.10.
207 Atlantic City VIII, 38.33, 71.36; VI/27:—0, 20.2, 35.19; 50, 16.05, 36.18; 100, 16.05, 36.38; 200, 15.95, 36.38; 300, 12.4, 35.59; 400, 11.05, 35.44; 600, 6.0, 35.07; 800, 4.6, 35.05; 1000, 4.1, 35.10.
208 Atlantic City IX, 38.22, 71.14; VI/27:—0, 20.8, 35.66; 50, 15.85, 35.77; 100, 14.8, 35.91; 200, 13.1, 35.84; 300, 11.15, 35.44; 400, 8.15, 35.21; 600, 5.75, 35.10; 800, 4.65, 35.01; 1000, 4.2, 35.08; 1200, 3.85, 35.09.
209 Atlantic City X, 38.12, 70.59; VI/28:—0, 20.4, 34.88; 25, 18.2, 35.33; 50, 14.3, 35.35; 100, 12.35, 35.41; 200, 10.15, 35.30; 300, 8.0, 35.14; 400, 6.1, 35.10; 600, 4.65, 35.05; 800, 4.1, 35.14; 1000, 3.95, 35.12; 1200, 3.75, 35.07.
210 Atlantic City XI, 38.03, 70.36; VI/28:—0, 22.3, 35.12; 25, 19.9, 35.28; 50, 14.4, 35.34; 100, 12.8, 35.73; 200, 9.95, 35.46 300, 7.75, 35.18; 400, 5.65, 35.00; 600, 4.7, 35.23; 800, 4.0, 35.03; 1000, 3.95, 35.01; 1200, 3.55, 34.99.
211 Atlantic City XII, 38.02, 70.03; VI/29:—0, 20.0, 34.16; 50, 17.95, 36.44; 100, 15.3, 35.99; 200, 11.7, 35.50; 300, 8.55, 35.14; 400, 6.4, 35.03; 600, 5.1, 35.07; 800, 4.05, 35.03; 1000, 3.9, 34.97; 1200, 3.65, 34.99.

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